

The LHC 750 GeV diphoton excess in supersymmetry with gauged baryon and lepton numbers

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Abstract

The significance of discovering the boson of 750 GeV is beyond finding a single heavy boson, because it may hint the location of the scale for new physics beyond the standard model which is the target of long-time exploration. There have been many models to explain the diphoton excess observed by the ATLAS and CMS collaborations and the BLMSSM is one of them. The BLMSSM is an extension of the minimal supersymmetric model where baryon and lepton numbers are local gauge symmetries. We analyze the decay channels $\Phi \rightarrow gg$, $\Phi \rightarrow \gamma\gamma$, $\Phi \rightarrow Z\gamma$, and $\Phi \rightarrow \bar{t}t$, VV ($V = Z, W$) with the mass of the CP-odd scalar $\Phi = A_B^0$ being around 750 GeV in this model. Within a certain parameter space, the scenario can account for the experimental data on the diphoton excess.

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I. INTRODUCTION

A new resonance with its mass around 750 GeV has been observed at the LHC at a center of mass energy of 13 TeV through the process $pp \rightarrow \Phi \rightarrow \gamma\gamma$ [1, 2]. If this observation is confirmed by subsequent experiments, the excess certainly manifests a signal of new physics beyond the standard model (BSM) and would be a milestone for high energy physics. Even though the standard model (SM) is very successful and almost all of its predictions are consistent with the standing experimental data, it is known that the SM is an effective theory of some underlying principles. So far nobody knows what the underlying principle is and a more bothersome situation is that there was not any hint about where the scale for the new physics should be. Therefore, besides looking for the SM Higgs which is the base of our SM, the second target of LHC is to search for new physics. The first target was fulfilled and the 125 GeV SM Higgs was discovered, thus the attentions of all physicists are turned to look for new physics, at least we need to determine the scale of new physics which would provide valuable information for building next generation of accelerators.

There have been many models beyond the SM and most of them possess a scalar or pseudoscalar boson(s) which may stand as the 750 GeV observed at LHC and be responsible for the diphoton excess. For example, in Refs. [3–7], a scalar particle with $m_\Phi = 750$ GeV is introduced which may decay into two photons as $\Phi \rightarrow 2\gamma$. Alternatively, in the framework of a minimal UV-complete model with a massive singlet pseudoscalar state, this diphoton excess is discussed [8]. Several models containing exotic fermions (a single vector-like quark with charge $2/3e$, a doublet of vector-like quarks, a vector-like generation including leptons) are considered, and these particles can contribute to the $\Phi \rightarrow 2\gamma$ [9]. With the supposition that vector-like quarks or leptons strongly couple to the heavy Higgs and photons or gluons in those new models, the diphoton resonance at a mass of 750 GeV [10] can be explained. Possible relations between the newly observed resonance and the dark matter are analyzed in the works of [11, 12]. There are also other works [13–41] which also research the diphoton excess reported by the the CMS and ATLAS collaborations. Up to now, there can be found hundreds of papers about it in arXiv.

As the simplest soft broken supersymmetry theory, the minimal supersymmetric extension

of the standard model (MSSM) [42, 43] has drawn quite attention of physicists for a long time. Furthermore, the matter-antimatter asymmetry in the universe requires that the baryon number (B) must be broken. Meanwhile, the lepton number should also be broken and as is well understood, existence of heavy Majorana neutrino(s) determines tiny neutrino masses via the seesaw mechanism [44–48] and also naturally explains the lepton number (L) violation. Gauging baryon and leptons actually provides a natural framework for the seesaw mechanism in the lepton sector, and the Peccei-Quinn mechanism solving the strong CP problem in the quark sector [49]. When the local B and L gauge symmetries are broken around TeV scale, one does not need a ‘desert region’ between the weak and GUT scales to adequately suppress the contribution of dimension 6 B-violating operators to proton decay [50]. Note that gauging B-L symmetry does not address this issue since dimension 6 operators mentioned above are B-L invariant [51]. Furthermore the simplest supersymmetric model with local $U(1)_{B-L}$ proposed in Refs. [52–55] cannot account for LHC experimental data of the 750 GeV resonance self-consistently unless we incorporate brand new matter superfields [30]. The authors of Refs. [56, 57] extended the MSSM by introducing two extra $U(1)$ gauge symmetries which correspond to baryon number B and lepton number L as the BLMSSM, then in the new theoretical framework they investigated decays of the SM-like CP-even Higgs. Since the newly introduced quarks in BLMSSM are vector-like, their masses can be well above 500 GeV without assuming a large coupling to the Higgs doublets in this model. Therefore, there does not exist a Landau pole for the Yukawa coupling [49–51]. Additionally, the authors of Refs. [50, 58–66] have done some studies in possible extension schemes of the SM where $U(1)_B$ and $U(1)_L$ are spontaneously broken around TeV scale.

In this work, we explore the possibilities that the 750 GeV diphoton event originates from decays of the CP-even scalars h_B^0 , H_B^0 and/or the CP-odd scalar A_B^0 which are induced by spontaneously breaking the local $U(1)_B$ symmetry. These bosons are different from the CP-even Higgs H^0 and CP-odd Higgs A^0 which belongs to the $SU(2)$ doublet before spontaneously breaking. Furthermore, since h_B^0 , H_B^0 and A_B^0 do not directly couple to the SM particles, so that their decays into SM particles can only be realized via loops which are suppressed by both the small couplings and the heavy intermediate agents (fermions or bosons). In order to fit the well determined experimental data of the 125 GeV Higgs [67–69],

we set the Yukawa coupling between the SM-like Higgs and exotic quarks into a suitable range, and assume the Yukawa coupling between Higgs and exotic leptons to be negligible. Our numerical result indicates that with a plausible parameter space, the CP-odd scalar A_B^0 in this model can naturally account for the experimental data on the 750 GeV excess measured by the ATLAS and CMS collaborations.

Our work is organized as follows. In section II, we briefly summarize the main ingredients of the BLMSSM, then present the mass squared matrices for the neutral scalar sectors and the mass matrices for exotic quarks, respectively. We discuss the decay widths for $\Phi \rightarrow \gamma\gamma$, VV ($V = Z, W$, $\Phi = h_B^0, H_B^0, A_B^0$) in section III. The numerical analyses are given in section IV, and eventually our summaries are made in the last section V. Some formulae are collected in Appendixes A-C.

II. A SUPERSYMMETRIC EXTENSION OF THE SM WITH B AND L BEING LOCAL GAUGE SYMMETRIES

When B and L are local gauge symmetries, one can enlarge the local gauge group of the SM to $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_B \otimes U(1)_L$. In the supersymmetric extension of the SM proposed in Refs. [56, 57], the exotic superfields include the new quarks $\hat{Q}_4 \sim (3, 2, 1/6, B_4, 0)$, $\hat{U}_4^c \sim (\bar{3}, 1, -2/3, -B_4, 0)$, $\hat{D}_4^c \sim (\bar{3}, 1, 1/3, -B_4, 0)$, $\hat{Q}_5^c \sim (\bar{3}, 2, -1/6, -(1+B_4), 0)$, $\hat{U}_5 \sim (3, 1, 2/3, 1+B_4, 0)$, $\hat{D}_5 \sim (3, 1, -1/3, 1+B_4, 0)$, and the new leptons $\hat{L}_4 \sim (1, 2, -1/2, 0, L_4)$, $\hat{E}_4^c \sim (1, 1, 1, 0, -L_4)$, $\hat{N}_4^c \sim (1, 1, 0, 0, -L_4)$, $\hat{L}_5^c \sim (1, 2, 1/2, 0, -(3+L_4))$, $\hat{E}_5 \sim (1, 1, -1, 0, 3+L_4)$, $\hat{N}_5 \sim (1, 1, 0, 0, 3+L_4)$ to cancel the B and L anomalies. The ‘brand new’ Higgs superfields $\hat{\Phi}_B \sim (1, 1, 0, 1, 0)$ and $\hat{\varphi}_B \sim (1, 1, 0, -1, 0)$ acquire nonzero vacuum expectation values (VEVs) to break baryon number symmetry spontaneously. Meanwhile, nonzero VEVs of $\hat{\Phi}_B$ and $\hat{\varphi}_B$ also induce large masses for the exotic quarks. In addition, the superfields $\hat{S}_L \sim (1, 1, 0, 0, -2)$, $\hat{\hat{S}}_L \sim (1, 1, 0, 0, 2)$, $\hat{\Phi}_L \sim (1, 1, 0, 0, -3)$ and $\hat{\varphi}_L \sim (1, 1, 0, 0, 3)$ acquire nonzero VEVs to break lepton number symmetry spontaneously. In addition, the VEVs of scalar components of $\hat{\Phi}_L$ and $\hat{\varphi}_L$ induce the TeV masses for 4th- and 5th-generation leptons, and the VEVs of scalar components of \hat{S}_L and $\hat{\hat{S}}_L$ produce the seesaw mechanism to result in tiny

neutrino masses. In order to avoid stability for the exotic quarks, the model also includes the superfields $\hat{X} \sim (1, 1, 0, 2/3 + B_4, 0)$ and $\hat{X}' \sim (1, 1, 0, -(2/3 + B_4), 0)$. Actually, the lightest one can stand as a dark matter candidate. The superpotential of the model is written as

$$\mathcal{W}_{BLMSSM} = \mathcal{W}_{MSSM} + \mathcal{W}_B + \mathcal{W}_L + \mathcal{W}_X, \quad (1)$$

where \mathcal{W}_{MSSM} is the superpotential of the MSSM, and

$$\begin{aligned} \mathcal{W}_B &= \lambda_Q \hat{Q}_4 \hat{Q}_5^c \hat{\Phi}_B + \lambda_U \hat{U}_4 \hat{U}_5^c \hat{\varphi}_B + \lambda_D \hat{D}_4 \hat{D}_5^c \hat{\varphi}_B + \mu_B \hat{\Phi}_B \hat{\varphi}_B \\ &\quad + Y_{u_4} \hat{Q}_4 \hat{H}_u \hat{U}_4^c + Y_{d_4} \hat{Q}_4 \hat{H}_d \hat{D}_4^c + Y_{u_5} \hat{Q}_5^c \hat{H}_d \hat{U}_5 + Y_{d_5} \hat{Q}_5^c \hat{H}_u \hat{D}_5, \\ \mathcal{W}_L &= \lambda_L \hat{L}_4 \hat{L}_5^c \hat{\Phi}_L + \lambda_E \hat{E}_4 \hat{E}_5^c \hat{\Phi}_L + \lambda_N \hat{N}_4 \hat{N}_5^c \hat{\Phi}_L + \mu_L \hat{\Phi}_L \hat{\varphi}_L \\ &\quad + Y_{e_4} \hat{L}_4 \hat{H}_d \hat{E}_4^c + Y_{\nu_4} \hat{L}_4 \hat{H}_u \hat{N}_4^c + Y_{e_5} \hat{L}_5^c \hat{H}_u \hat{E}_5 + Y_{\nu_5} \hat{L}_5^c \hat{H}_d \hat{N}_5 \\ &\quad + Y_\nu \hat{L} \hat{H}_u \hat{N}^c + \lambda_{N^c} \hat{N}^c \hat{N}^c \hat{S}_L + \mu_S \hat{S}_L \hat{\bar{S}}_L, \\ \mathcal{W}_X &= \lambda_1 \hat{Q} \hat{Q}_5^c \hat{X} + \lambda_2 \hat{U} \hat{U}_5^c \hat{X}' + \lambda_3 \hat{D} \hat{D}_5^c \hat{X}' + \mu_X \hat{X} \hat{X}'. \end{aligned} \quad (2)$$

In the superpotential given above, the exotic quarks obtain TeV scale masses after Φ_B , φ_B acquire nonzero VEVs. Correspondingly, the soft breaking terms are generally given as

$$\begin{aligned} \mathcal{L}_{soft} &= \mathcal{L}_{soft}^{MSSM} - (m_{\tilde{N}^c}^2)_{IJ} \tilde{N}_I^{c*} \tilde{N}_J^c - m_{\tilde{Q}_4}^2 \tilde{Q}_4^\dagger \tilde{Q}_4 - m_{\tilde{U}_4}^2 \tilde{U}_4^{c*} \tilde{U}_4^c - m_{\tilde{D}_4}^2 \tilde{D}_4^{c*} \tilde{D}_4^c \\ &\quad - m_{\tilde{Q}_5}^2 \tilde{Q}_5^{c\dagger} \tilde{Q}_5^c - m_{\tilde{U}_5}^2 \tilde{U}_5^* \tilde{U}_5 - m_{\tilde{D}_5}^2 \tilde{D}_5^* \tilde{D}_5 - m_{\tilde{L}_4}^2 \tilde{L}_4^\dagger \tilde{L}_4 - m_{\tilde{\nu}_4}^2 \tilde{\nu}_4^{c*} \tilde{\nu}_4^c \\ &\quad - m_{\tilde{E}_4}^2 \tilde{e}_4^{c*} \tilde{e}_4^c - m_{\tilde{L}_5}^2 \tilde{L}_5^{c\dagger} \tilde{L}_5^c - m_{\tilde{\nu}_5}^2 \tilde{\nu}_5^* \tilde{\nu}_5 - m_{\tilde{E}_5}^2 \tilde{e}_5^* \tilde{e}_5 - m_{\Phi_B}^2 \Phi_B^* \Phi_B \\ &\quad - m_{\varphi_B}^2 \varphi_B^* \varphi_B - m_{\Phi_L}^2 \Phi_L^* \Phi_L - m_{\varphi_L}^2 \varphi_L^* \varphi_L - (m_B \lambda_B \lambda_B + m_L \lambda_L \lambda_L + h.c.) \\ &\quad + \{ A_{u_4} Y_{u_4} \tilde{Q}_4 H_u \tilde{U}_4^c + A_{d_4} Y_{d_4} \tilde{Q}_4 H_d \tilde{D}_4^c + A_{u_5} Y_{u_5} \tilde{Q}_5^c H_d \tilde{U}_5 + A_{d_5} Y_{d_5} \tilde{Q}_5^c H_u \tilde{D}_5 \\ &\quad + A_{BQ} \lambda_Q \tilde{Q}_4 \tilde{Q}_5^c \Phi_B + A_{BU} \lambda_U \tilde{U}_4 \tilde{U}_5^c \varphi_B + A_{BD} \lambda_D \tilde{D}_4 \tilde{D}_5^c \varphi_B + B_B \mu_B \Phi_B \varphi_B + h.c. \} \\ &\quad + \{ A_{e_4} Y_{e_4} \tilde{L}_4 H_d \tilde{E}_4^c + A_{N_4} Y_{N_4} \tilde{L}_4 H_u \tilde{N}_4^c + A_{e_5} Y_{e_5} \tilde{L}_5^c H_u \tilde{E}_5 + A_{N_5} Y_{N_5} \tilde{L}_5^c H_d \tilde{N}_5 \\ &\quad + A_N Y_N \tilde{L} H_u \tilde{N}^c + A_{LL} \lambda_L \tilde{L}_4 \tilde{L}_5^c \varphi_L + A_{LE} \lambda_E \tilde{E}_4 \tilde{E}_5^c \Phi_L + A_{LN} \lambda_N \tilde{N}_4^c \tilde{N}_5^c \Phi_L \\ &\quad + B_L \mu_L \Phi_L \varphi_L + A_{N^c} \lambda_{N^c} \tilde{N}^c \tilde{N}^c S_L + B_S \mu_S S_L \bar{S}_L + h.c. \} \\ &\quad + \{ A_1 \lambda_1 \tilde{Q} \tilde{Q}_5^c X + A_2 \lambda_2 \tilde{U} \tilde{U}_5^c X' + A_3 \lambda_3 \tilde{D} \tilde{D}_5^c X' + B_X \mu_X X X' + h.c. \}, \end{aligned} \quad (3)$$

where $\mathcal{L}_{soft}^{MSSM}$ is the soft breaking terms for the MSSM, λ_B , λ_L are gauginos of $U(1)_B$ and $U(1)_L$, respectively. After the $SU(2)_L$ doublets H_u , H_d and $SU(2)_L$ singlets Φ_B , φ_B , Φ_L , φ_L

acquire nonzero VEVs: v_u , v_d , v_B , \bar{v}_B , and v_L , \bar{v}_L , then we have

$$\begin{aligned}
H_u &= \begin{pmatrix} H_u^+ \\ \frac{1}{\sqrt{2}}(v_u + H_u^0 + iP_u^0) \end{pmatrix}, \\
H_d &= \begin{pmatrix} \frac{1}{\sqrt{2}}(v_d + H_d^0 + iP_d^0) \\ H_d^- \end{pmatrix}, \\
\Phi_B &= \frac{1}{\sqrt{2}}(v_B + \Phi_B^0 + iP_B^0), \\
\varphi_B &= \frac{1}{\sqrt{2}}(\bar{v}_B + \varphi_B^0 + i\bar{P}_B^0), \\
\Phi_L &= \frac{1}{\sqrt{2}}(v_L + \Phi_L^0 + iP_L^0), \\
\varphi_L &= \frac{1}{\sqrt{2}}(\bar{v}_L + \varphi_L^0 + i\bar{P}_L^0),
\end{aligned} \tag{4}$$

and the local gauge symmetry $SU(2)_L \otimes U(1)_Y \otimes U(1)_B \otimes U(1)_L$ is broken down to the electromagnetic symmetry $U(1)_{em}$, where

$$G^\pm = \cos \beta H_d^\pm + \sin \beta H_u^\pm, \tag{5}$$

denotes the charged Goldstone boson, and

$$\begin{aligned}
G^0 &= \cos \beta P_d^0 + \sin \beta P_u^0, \\
G_B^0 &= \cos \beta_B P_B^0 + \sin \beta_B \bar{P}_B^0, \\
G_L^0 &= \cos \beta_L P_L^0 + \sin \beta_L \bar{P}_L^0,
\end{aligned} \tag{6}$$

denote the neutral Goldstone bosons, respectively. Here $\tan \beta = v_u/v_d$, $\tan \beta_B = \bar{v}_B/v_B$ and $\tan \beta_L = \bar{v}_L/v_L$. Correspondingly, the physical neutral pseudoscalar fields are

$$\begin{aligned}
A^0 &= -\sin \beta P_d^0 + \cos \beta P_u^0, \\
A_B^0 &= -\sin \beta_B P_B^0 + \cos \beta_B \bar{P}_B^0, \\
A_L^0 &= -\sin \beta_L P_L^0 + \cos \beta_L \bar{P}_L^0.
\end{aligned} \tag{7}$$

At the tree level, the masses for those particles are respectively formulated as

$$m_{A^0}^2 = \frac{B\mu}{\cos \beta \sin \beta},$$

$$\begin{aligned} m_{A_B^0}^2 &= \frac{B_B \mu_B}{\cos \beta_B \sin \beta_B}, \\ m_{A_L^0}^2 &= \frac{B_L \mu_L}{\cos \beta_L \sin \beta_L}. \end{aligned} \quad (8)$$

Meanwhile the charged Higgs is

$$H^\pm = -\sin \beta H_d^\pm + \cos \beta H_u^\pm, \quad (9)$$

with the tree level mass square

$$m_{H^\pm}^2 = m_{A^0}^2 + m_W^2. \quad (10)$$

In the two Higgs doublet sector, the mass square matrix of neutral CP-even Higgs is diagonalized by a rotation

$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} H_d^0 \\ H_u^0 \end{pmatrix}, \quad (11)$$

where h^0 is the lightest neutral CP-even Higgs.

In the basis (Φ_B^0, φ_B^0) , the mass square matrix is

$$\mathcal{M}_{EB}^2 = \begin{pmatrix} m_{Z_B}^2 \cos^2 \beta_B + m_{A_B^0}^2 \sin^2 \beta_B, & (m_{Z_B}^2 + m_{A_B^0}^2) \cos \beta_B \sin \beta_B \\ (m_{Z_B}^2 + m_{A_B^0}^2) \cos \beta_B \sin \beta_B, & m_{Z_B}^2 \sin^2 \beta_B + m_{A_B^0}^2 \cos^2 \beta_B \end{pmatrix}, \quad (12)$$

where $m_{Z_B}^2 = g_B^2(v_B^2 + \bar{v}_B^2)$ is mass square of the neutral $U(1)_B$ gauge boson Z_B . Defining the mixing angle α_B through

$$\tan 2\alpha_B = \frac{m_{Z_B}^2 + m_{A_B^0}^2}{m_{Z_B}^2 - m_{A_B^0}^2} \tan 2\beta_B, \quad (13)$$

we obtain two mass eigenstates as

$$\begin{pmatrix} H_B^0 \\ h_B^0 \end{pmatrix} = \begin{pmatrix} \cos \alpha_B & \sin \alpha_B \\ -\sin \alpha_B & \cos \alpha_B \end{pmatrix} \begin{pmatrix} \Phi_B^0 \\ \varphi_B^0 \end{pmatrix}. \quad (14)$$

Similarly the mass square matrix for (Φ_L^0, φ_L^0) is written as

$$\mathcal{M}_{EL}^2 = \begin{pmatrix} m_{Z_L}^2 \cos^2 \beta_L + m_{A_L^0}^2 \sin^2 \beta_L, & (m_{Z_L}^2 + m_{A_L^0}^2) \cos \beta_L \sin \beta_L \\ (m_{Z_L}^2 + m_{A_L^0}^2) \cos \beta_L \sin \beta_L, & m_{Z_L}^2 \sin^2 \beta_L + m_{A_L^0}^2 \cos^2 \beta_L \end{pmatrix}, \quad (15)$$

with $m_{Z_L}^2 = 4g_L^2(v_L^2 + \bar{v}_L^2)$ denoting mass square of the neutral $U(1)_L$ gauge boson Z_L . We can obtain two mass eigenstates as

$$\begin{pmatrix} H_L^0 \\ h_L^0 \end{pmatrix} = \begin{pmatrix} \cos \alpha_L & \sin \alpha_L \\ -\sin \alpha_L & \cos \alpha_L \end{pmatrix} \begin{pmatrix} \Phi_L^0 \\ \varphi_L^0 \end{pmatrix}. \quad (16)$$

The mass matrix for the exotic quarks of charge 2/3 which are four-component Dirac spinors is

$$-\mathcal{L}_{t'}^{mass} = \begin{pmatrix} \bar{t}'_{4R}, & \bar{t}'_{5R} \end{pmatrix} \begin{pmatrix} \frac{1}{\sqrt{2}}\lambda_Q v_B, & -\frac{1}{\sqrt{2}}Y_{u_5} v_d \\ -\frac{1}{\sqrt{2}}Y_{u_4} v_u, & \frac{1}{\sqrt{2}}\lambda_U \bar{v}_B \end{pmatrix} \begin{pmatrix} t'_{4L} \\ t'_{5L} \end{pmatrix} + h.c. \quad (17)$$

Performing unitary transformations U_t and W_t

$$\begin{pmatrix} t_{4L} \\ t_{5L} \end{pmatrix} = U_t^\dagger \cdot \begin{pmatrix} t'_{4L} \\ t'_{5L} \end{pmatrix}, \quad \begin{pmatrix} t_{4R} \\ t_{5R} \end{pmatrix} = W_t^\dagger \cdot \begin{pmatrix} t'_{4R} \\ t'_{5R} \end{pmatrix}, \quad (18)$$

we diagonalize the mass matrix for the vector quarks of charge 2/3:

$$W_t^\dagger \cdot \begin{pmatrix} \frac{1}{\sqrt{2}}\lambda_Q v_B, & -\frac{1}{\sqrt{2}}Y_{u_5} v_d \\ -\frac{1}{\sqrt{2}}Y_{u_4} v_u, & \frac{1}{\sqrt{2}}\lambda_U \bar{v}_B \end{pmatrix} \cdot U_t = \text{diag}(m_{t_4}, m_{t_5}). \quad (19)$$

Similarly we write the mass matrix for the exotic quarks of charge -1/3 as

$$-\mathcal{L}_{b'}^{mass} = \begin{pmatrix} \bar{b}'_{4R}, & \bar{b}'_{5R} \end{pmatrix} \begin{pmatrix} -\frac{1}{\sqrt{2}}\lambda_Q v_B, & -\frac{1}{\sqrt{2}}Y_{d_5} v_u \\ -\frac{1}{\sqrt{2}}Y_{d_4} v_d, & \frac{1}{\sqrt{2}}\lambda_D \bar{v}_B \end{pmatrix} \begin{pmatrix} b'_{4L} \\ b'_{5L} \end{pmatrix} + h.c. \quad (20)$$

Adopting unitary transformations

$$\begin{pmatrix} b_{4L} \\ b_{5L} \end{pmatrix} = U_b^\dagger \cdot \begin{pmatrix} b'_{4L} \\ b'_{5L} \end{pmatrix}, \quad \begin{pmatrix} b_{4R} \\ b_{5R} \end{pmatrix} = W_b^\dagger \cdot \begin{pmatrix} b'_{4R} \\ b'_{5R} \end{pmatrix}, \quad (21)$$

one can diagonalize the mass matrix for the vector quarks of charge -1/3 as

$$W_b^\dagger \cdot \begin{pmatrix} -\frac{1}{\sqrt{2}}\lambda_Q v_B, & -\frac{1}{\sqrt{2}}Y_{d_5} v_u \\ -\frac{1}{\sqrt{2}}Y_{d_4} v_d, & \frac{1}{\sqrt{2}}\lambda_D \bar{v}_B \end{pmatrix} \cdot U_b = \text{diag}(m_{b_4}, m_{b_5}). \quad (22)$$

Using the superpotential in Eq. (1) and introducing the soft breaking terms, we write the mass square matrices for the exotic scalar quarks as

$$-\mathcal{L}_{\widetilde{EQ}}^{mass} = \tilde{t}^{\dagger} \cdot \mathcal{M}_{\tilde{t}'}^2 \cdot \tilde{t}' + \tilde{b}^{\dagger} \cdot \mathcal{M}_{\tilde{b}'}^2 \cdot \tilde{b}' \quad (23)$$

with $\tilde{t}^T = (\tilde{Q}_4^1, \tilde{U}_4^{c*}, \tilde{Q}_5^{2c*}, \tilde{U}_5)$, $\tilde{b}^T = (\tilde{Q}_4^2, \tilde{D}_4^{c*}, \tilde{Q}_5^{1c*}, \tilde{D}_5^*)$. The concrete expressions for the 4×4 mass square matrices $\mathcal{M}_{\tilde{t}}^2$, $\mathcal{M}_{\tilde{b}}^2$, and the couplings between the neutral Higgs and exotic scalar quarks are collected elsewhere [61], the couplings between heavy neutral Higgs and exotic quarks can also be found there.

The mass matrix for exotic neutrinos which are four-component spinors, is

$$-\mathcal{L}_{\nu'}^{mass} = \begin{pmatrix} \bar{\nu}'_{4R}, & \bar{\nu}'_{5R} \end{pmatrix} \begin{pmatrix} \frac{1}{\sqrt{2}}\lambda_L \bar{\nu}_L, & -\frac{1}{\sqrt{2}}Y_{\nu_5} v_d \\ -\frac{1}{\sqrt{2}}Y_{\nu_4} v_u, & \frac{1}{\sqrt{2}}\lambda_N v_L \end{pmatrix} \begin{pmatrix} \nu'_{4L} \\ \nu'_{5L} \end{pmatrix} + h.c. \quad (24)$$

Similarly the mass matrix for exotic charged leptons is

$$-\mathcal{L}_{e'}^{mass} = \begin{pmatrix} \bar{e}'_{4R}, & \bar{e}'_{5R} \end{pmatrix} \begin{pmatrix} -\frac{1}{\sqrt{2}}\lambda_L \bar{\nu}_L, & -\frac{1}{\sqrt{2}}Y_{e_5} v_u \\ -\frac{1}{\sqrt{2}}Y_{e_4} v_d, & \frac{1}{\sqrt{2}}\lambda_E v_L \end{pmatrix} \begin{pmatrix} e'_{4L} \\ e'_{5L} \end{pmatrix} + h.c. \quad (25)$$

Including those ‘new’ particles mentioned above, the evaluations of gauge couplings are described by the renormalization group equations (RGEs) [70, 71]

$$\begin{aligned} \frac{dg_i}{dt} &= \frac{1}{2}\beta_{g_i}, \quad (i = 1, 2, 3), \\ \frac{dg_B}{dt} &= \frac{1}{2}\beta_{g_B}, \quad \frac{dg_L}{dt} = \frac{1}{2}\beta_{g_L}, \end{aligned} \quad (26)$$

where $t = \ln Q^2$. Adopting the step approximation in contributions from new particles to the β functions [72], we then find

$$\begin{aligned} \beta_{g_3} &= -\frac{g_3^3}{16\pi^2} \left\{ \left(11 - \frac{10}{3} - \frac{2}{3}\theta_t \right) - \frac{1}{3} \sum_{\alpha=4}^5 (2\theta_{Q_\alpha} + \theta_{U_\alpha} + \theta_{D_\alpha}) - 2\theta_{\tilde{g}} \right. \\ &\quad \left. - \frac{1}{24} \sum_{i=1}^5 (2\theta_{\tilde{Q}_i} + \theta_{\tilde{U}_i} + \theta_{\tilde{D}_i}) \right\}, \\ \beta_{g_2} &= -\frac{g_2^3}{16\pi^2} \left\{ \left(\frac{22}{3} - 3 - \theta_t \right) - \frac{1}{3}\theta_{A^0} - \frac{4}{3}\theta_{\tilde{W}} - \frac{2}{3}\theta_{\tilde{H}} - \frac{1}{3} \sum_{\alpha=4}^5 (\theta_{L_\alpha} + 3\theta_{Q_\alpha}) \right. \\ &\quad \left. - \frac{1}{24} \sum_{i=1}^5 (\theta_{\tilde{L}_i} + 3\theta_{\tilde{Q}_i}) \right\}, \\ \beta_{g_1} &= \frac{g_1^3}{16\pi^2} \left\{ \left(\frac{51}{9} + \theta_t \right) + \frac{1}{3}\theta_{A^0} + \frac{2}{3}\theta_{\tilde{H}} + \frac{4}{3} \sum_{\alpha=4}^5 \left(\frac{1}{4}\theta_{L_\alpha} + \frac{1}{2}\theta_{E_\alpha} + \frac{1}{12}\theta_{Q_\alpha} + \frac{2}{3}\theta_{U_\alpha} \right. \right. \\ &\quad \left. \left. + \frac{1}{6}\theta_{D_\alpha} \right) + \frac{1}{6} \sum_{i=1}^5 \left(\frac{1}{4}\theta_{\tilde{L}_i} + \frac{1}{2}\theta_{\tilde{E}_i} + \frac{1}{12}\theta_{\tilde{Q}_i} + \frac{2}{3}\theta_{\tilde{U}_i} + \frac{1}{6}\theta_{\tilde{D}_i} \right) \right\}, \\ \beta_{g_B} &= \frac{g_B^3}{16\pi^2} \left\{ \left(2 + \frac{2}{3}\theta_t \right) + \frac{1}{36} \sum_{i=1}^3 (2\theta_{\tilde{Q}_i} + \theta_{\tilde{U}_i} + \theta_{\tilde{D}_i}) + \frac{1}{3} (2\theta_{\tilde{\Phi}_B} + 2\theta_{\tilde{\phi}_B} \right. \end{aligned}$$

$$\begin{aligned}
& +\frac{1}{4}\theta_{\Phi_B} + \frac{1}{4}\theta_{\phi_B} \Big) + \left(\frac{1}{3} + \frac{B_4}{2}\right)^2 \left(2\theta_{\tilde{X}} + 2\theta_{\tilde{X}'} + \frac{1}{4}\theta_X + \frac{1}{4}\theta_{X'}\right) \\
& + B_4^2 \left(4\theta_{Q_4} + 2\theta_{U_4} + 2\theta_{D_4} + \frac{1}{2}\theta_{\tilde{Q}_4} + \frac{1}{4}\theta_{\tilde{U}_4} + \frac{1}{4}\theta_{\tilde{D}_4}\right) \\
& + (1 + B_4)^2 \left(4\theta_{Q_5} + 2\theta_{U_5} + 2\theta_{D_5} + \frac{1}{2}\theta_{\tilde{Q}_5} + \frac{1}{4}\theta_{\tilde{U}_5} + \frac{1}{4}\theta_{\tilde{D}_5}\right) \Big\} , \\
\beta_{g_L} = & \frac{g_L^3}{16\pi^2} \left\{ 6 + \frac{2}{3} \sum_{i=1}^3 \theta_{N_i} + \frac{1}{12} \sum_{i=1}^3 \left(2\theta_{\tilde{L}_i} + \theta_{\tilde{E}_i} + \theta_{\tilde{N}_i} \right) + \frac{4}{3} \left(2\theta_{\tilde{S}_L} + 2\theta_{\tilde{S}_L} \right. \right. \\
& + \frac{1}{4}\theta_{S_L} + \frac{1}{4}\theta_{\tilde{S}_L} \Big) + 3 \left(2\theta_{\Phi_L} + 2\theta_{\tilde{\Phi}_L} + \frac{1}{4}\theta_{\Phi_L} + \frac{1}{4}\theta_{\phi_L} \right) \\
& + \frac{L_4^2}{3} \left(4\theta_{L_4} + 2\theta_{N_4} + 2\theta_{E_4} + \frac{1}{2}\theta_{\tilde{L}_4} + \frac{1}{4}\theta_{\tilde{N}_4} + \frac{1}{4}\theta_{\tilde{E}_4} \right) \\
& \left. + \frac{(1 + L_4)^2}{3} \left(4\theta_{L_5} + 2\theta_{N_5} + 2\theta_{E_5} + \frac{1}{2}\theta_{\tilde{L}_5} + \frac{1}{4}\theta_{\tilde{N}_5} + \frac{1}{4}\theta_{\tilde{E}_5} \right) \right\} , \tag{27}
\end{aligned}$$

with

$$\theta_a = \theta(\ln \frac{Q^2}{m_a^2}) = \begin{cases} 1 & \text{for } Q > m_a , \\ 0 & \text{for } Q \leq m_a . \end{cases} \tag{28}$$

To simplify our discussion below, we assume new particles with masses of roughly same order Λ_{NP} . Using the evolution equations in Eq. (26), we obtain the effective couplings for α_i ($i = 3, 2, 1$) as

$$\begin{aligned}
\alpha_3(\Lambda) &= \begin{cases} \frac{\alpha_3(m_Z)}{1 + \frac{23}{3} \frac{\alpha_3(m_Z)}{4\pi} \ln \frac{\Lambda^2}{m_Z^2}} , & m_Z < \Lambda \leq m_t \\ \frac{\alpha_3(m_t)}{1 + 7 \frac{\alpha_3(m_t)}{4\pi} \ln \frac{\Lambda^2}{m_t^2}} , & m_t < \Lambda \leq \Lambda_{NP} \\ \frac{\alpha_3(\Lambda_{NP})}{1 + \frac{3}{2} \frac{\alpha_3(\Lambda_{NP})}{4\pi} \ln \frac{\Lambda^2}{\Lambda_{NP}^2}} , & \Lambda > \Lambda_{NP} \end{cases} , \\
\alpha_2(\Lambda) &= \begin{cases} \frac{\alpha_2(m_Z)}{1 + \frac{13}{3} \frac{\alpha_2(m_Z)}{4\pi} \ln \frac{\Lambda^2}{m_Z^2}} , & m_Z < \Lambda \leq m_t \\ \frac{\alpha_2(m_t)}{1 + \frac{10}{3} \frac{\alpha_2(m_t)}{4\pi} \ln \frac{\Lambda^2}{m_t^2}} , & m_t < \Lambda \leq \Lambda_{NP} \\ \frac{\alpha_2(\Lambda_{NP})}{1 - \frac{5}{2} \frac{\alpha_2(\Lambda_{NP})}{4\pi} \ln \frac{\Lambda^2}{\Lambda_{NP}^2}} , & \Lambda > \Lambda_{NP} \end{cases} , \\
\alpha_1(\Lambda) &= \begin{cases} \frac{\alpha_1(m_Z)}{1 - \frac{51}{9} \frac{\alpha_1(m_Z)}{4\pi} \ln \frac{\Lambda^2}{m_Z^2}} , & m_Z < \Lambda \leq m_t \\ \frac{\alpha_1(m_t)}{1 - \frac{20}{3} \frac{\alpha_1(m_t)}{4\pi} \ln \frac{\Lambda^2}{m_t^2}} , & m_t < \Lambda \leq \Lambda_{NP} \\ \frac{\alpha_1(\Lambda_{NP})}{1 - \frac{27}{2} \frac{\alpha_1(\Lambda_{NP})}{4\pi} \ln \frac{\Lambda^2}{\Lambda_{NP}^2}} , & \Lambda > \Lambda_{NP} \end{cases} , \tag{29}
\end{aligned}$$

with $\alpha_i = g_i^2/(4\pi)$. Obviously there is no Landau singularity in the strong interaction coupling α_3 as $\Lambda > \Lambda_{NP}$, the Landau singularities for $\alpha_{1,2}$ are approached as

$$\begin{aligned}\Lambda_{LS}^{(1)} &\simeq \Lambda_{NP} \exp \left[\frac{4\pi}{27\alpha_1(\Lambda_{NP})} \right], \\ \Lambda_{LS}^{(2)} &\simeq \Lambda_{NP} \exp \left[\frac{4\pi}{5\alpha_2(\Lambda_{NP})} \right].\end{aligned}\quad (30)$$

Choosing $\alpha(m_Z) = 1/128$, $s_W^2(m_Z) = 0.23$, $m_t = 174$ GeV, $m_Z = 91.19$ GeV, $\Lambda_{NP} = 3$ TeV, we get $\Lambda_{LS}^{(1)} \simeq 4.7 \times 10^{22}$ GeV and $\Lambda_{LS}^{(2)} \simeq 5.6 \times 10^{37}$ GeV which is above the Planck scale $\Lambda_{Planck} \sim 10^{19}$ GeV, so α_1 and α_2 is safe, i.e. not bothered by the singularity.

Furthermore, the Landau singularities of $\alpha_{B,L}$ are written as

$$\begin{aligned}\Lambda_{LS}^{(B)} &\simeq \Lambda_{NP} \exp \left[\frac{2\pi}{b_B \alpha_B(\Lambda_{NP})} \right], \\ \Lambda_{LS}^{(L)} &\simeq \Lambda_{NP} \exp \left[\frac{2\pi}{b_L \alpha_L(\Lambda_{NP})} \right],\end{aligned}\quad (31)$$

with

$$\begin{aligned}b_B &= \frac{9}{2} \left[1 + \left(\frac{1}{3} + B_4 \right)^2 + 2B_4^2 + 2(1 + B_4)^2 \right], \\ b_L &= \frac{57}{2} + 3L_4^2 + 3(1 + L_4)^2.\end{aligned}\quad (32)$$

Choose $B_4 = L_4 = 0$, $\Lambda_{NP} = 3$ TeV, $g_B(\Lambda_{NP}) = 0.35$ and $g_L(\Lambda_{NP}) = 0.2$, one obtains $\Lambda_{LS}^{(B)} \simeq 3.0 \times 10^{23}$ GeV, $\Lambda_{LS}^{(L)} \simeq 4.9 \times 10^{30}$ GeV, respectively.

III. $gg \rightarrow \Phi$ AND $\Phi \rightarrow \gamma\gamma, ZZ, Z\gamma, WW, t\bar{t}$

It is well known for quite some while that radiative corrections modify the tree level mass square matrix of neutral Higgs substantially in the MSSM, where the main effect originates from one-loop diagrams involving the top quark and its scalar partners $\tilde{t}_{1,2}$ [73]. In order to obtain masses of the neutral CP-even Higgs reasonably, we should include the radiative corrections from exotic fermions and corresponding supersymmetric partners in the our model. Then, the mass square matrix for the neutral CP-even Higgs in the basis (H_d^0, H_u^0) is written as

$$\mathcal{M}_{even}^2 = \begin{pmatrix} M_{11}^2 + \Delta_{11} & M_{12}^2 + \Delta_{12} \\ M_{12}^2 + \Delta_{12} & M_{22}^2 + \Delta_{22} \end{pmatrix}, \quad (33)$$

where

$$\begin{aligned}
M_{11}^2 &= m_Z^2 \cos^2 \beta + m_{A^0}^2 \sin^2 \beta , \\
M_{12}^2 &= -(m_Z^2 + m_{A^0}^2) \sin \beta \cos \beta , \\
M_{22}^2 &= m_Z^2 \sin^2 \beta + m_{A^0}^2 \cos^2 \beta ,
\end{aligned} \tag{34}$$

and m_{A^0} stands for the pseudo-scalar Higgs mass at tree level. In this model the radiative corrections originate from the MSSM sector, exotic fermions and their scalar partners respectively:

$$\begin{aligned}
\Delta_{11} &= \Delta_{11}^{MSSM} + \Delta_{11}^B + \Delta_{11}^L , \\
\Delta_{12} &= \Delta_{12}^{MSSM} + \Delta_{12}^B + \Delta_{12}^L , \\
\Delta_{22} &= \Delta_{22}^{MSSM} + \Delta_{22}^B + \Delta_{22}^L .
\end{aligned} \tag{35}$$

The concrete expressions for Δ_{11}^{MSSM} , Δ_{12}^{MSSM} , Δ_{22}^{MSSM} at two-loop level can be found in literatures [74–77], whereas the one-loop radiative corrections from the exotic quark fields to Δ_{11}^B , Δ_{12}^B , Δ_{22}^B are formulated in Appendix A. Considered that the VEVs of scalar components of $\hat{\Phi}_L$ and $\hat{\varphi}_L$ can induce the TeV masses to the exotic leptons, we could choose sufficiently small exotic lepton Yukawa couplings and then the radiative corrections from exotic lepton fields for Δ_{11}^L , Δ_{12}^L , Δ_{22}^L can be ignored in our following numerical computations.

One of the most stringent constraints on the parameter space of the BLMSSM is that the mass square matrix in Eq. (33) should produce an eigenvalue around $(125 \text{ GeV})^2$ as mass square of the lightest neutral CP-even Higgs. The current combination of the ATLAS and CMS data gives [67–69]:

$$m_{h^0} = 125.09 \pm 0.24 \text{ GeV} , \tag{36}$$

and this requirement restricts the parameter space of the BLMSSM strongly. Besides the observed signals for the diphoton and ZZ^* , WW^* , $b\bar{b}$ channels of the 125 GeV Higgs obtained by the ATLAS and CMS collaborations are quantified by the ratios [61]

$$\begin{aligned}
R_{\gamma\gamma} &= \frac{\Gamma_{NP}(h^0 \rightarrow gg)\Gamma_{NP}(h^0 \rightarrow \gamma\gamma)}{\Gamma_{SM}(h^0 \rightarrow gg)\Gamma_{SM}(h^0 \rightarrow \gamma\gamma)} , \\
R_{VV^*} &= \frac{\Gamma_{NP}(h^0 \rightarrow gg)\Gamma_{NP}(h^0 \rightarrow VV^*)}{\Gamma_{SM}(h^0 \rightarrow gg)\Gamma_{SM}(h^0 \rightarrow VV^*)} , \quad (V = Z, W) .
\end{aligned} \tag{37}$$

The weighted averages of the ratios are [78–87]:

$$\begin{aligned}\text{ATLAS + CMS : } R_{\gamma\gamma} &= 1.19 \pm 0.31 , \\ \text{ATLAS + CMS : } R_{VV^*} &= 0.86 \pm 0.16 .\end{aligned}\tag{38}$$

In the following numerical computations, we use the weighted averages of the ratios within 2σ tolerance to constrain the parameter space.

From Eq. (12) and Eq. (15), the masses of ‘brand new’ neutral Higgs satisfy tree-level relations

$$\begin{aligned}m_{Z_B}^2 + m_{A_B^0}^2 &= m_{h_B^0}^2 + m_{H_B^0}^2 , \\ m_{Z_B}^2 m_{A_B^0}^2 \cos^2 2\theta_B &= m_{h_B^0}^2 m_{H_B^0}^2 , \\ m_{Z_L}^2 + m_{A_L^0}^2 &= m_{h_L^0}^2 + m_{H_L^0}^2 , \\ m_{Z_L}^2 m_{A_L^0}^2 \cos^2 2\theta_L &= m_{h_L^0}^2 m_{H_L^0}^2 .\end{aligned}\tag{39}$$

When the radiative corrections do not modified those relations drastically, there are several particularly interesting predictions:

$$\begin{aligned}m_{h_B^0} &\leq (m_{A_B^0}, m_{Z_B}) \leq m_{H_B^0} , \\ m_{h_B^0} &\leq \min(m_{A_B^0}, m_{Z_B}) |\cos 2\theta_B| \leq m_{Z_B} , \\ m_{h_L^0} &\leq (m_{A_L^0}, m_{Z_L}) \leq m_{H_L^0} , \\ m_{h_L^0} &\leq \min(m_{A_L^0}, m_{Z_L}) |\cos 2\theta_L| \leq m_{Z_L} .\end{aligned}\tag{40}$$

It is not worth surprising because there are similar tree-level relations in the MSSM which are modified drastically by the radiative corrections originating from large Yukawa couplings of top and its superpartners.

Because of the Landau-Yang theorem [88, 89], the 750 GeV resonance with diphoton decay mode cannot be interpreted as the massive gauge bosons Z_B , Z_L in this model. In addition, the 750 GeV resonance generally cannot be interpreted as H^0 , A^0 which are originated from $SU(2)$ doublets since we do not find the resonance in the WW , ZZ , and $t\bar{t}$ channels. For the points mentioned above, the potential candidate in the model considered here for the 750 GeV resonance is possibly one of $h_{B,L}^0$, $H_{B,L}^0$, $A_{B,L}^0$. Nevertheless the leading order

contributions to $\Phi \rightarrow gg$ emerge at the 3-loop level, if we took the 750 GeV resonance as one of $\Phi = h_L^0, H_L^0, A_L^0$. By the mass relations given in Eq. (40), we reasonably choose one of $\Phi = h_B^0, A_B^0$ to be the 750 GeV resonance and $m_{Z_{B,L}} \geq 1$ TeV in accord with the experimental constraint set by Z' searching at colliders [90].

The 750 GeV scalar is produced mainly through the gluon fusion at the LHC. In the supersymmetric extension of the SM, the LO decay width for the process $\Phi \rightarrow gg$ ($\Phi = H^0, h_B^0, H_B^0$) is given as (see Refs. [91–95] and references therein)

$$\Gamma_{NP}(\Phi \rightarrow gg) = \frac{G_F \alpha_s^2 m_\Phi^3}{64\sqrt{2}\pi^3} \left| \sum_q g_{\Phi qq} A_{1/2}(x_q) + \sum_{\tilde{q}} g_{\Phi \tilde{q} \tilde{q}} \frac{m_Z^2}{m_{\tilde{q}}^2} A_0(x_{\tilde{q}}) \right|^2, \quad (41)$$

with $x_a = m_a^2/(4m_\Phi^2)$. In addition, $q = t, b, t_4, t_5, b_4, b_5$ and $\tilde{q} = \tilde{t}_{1,2}, \tilde{b}_{1,2}, \tilde{\mathcal{U}}_i, \tilde{\mathcal{D}}_i$ ($i = 1, 2, 3, 4$). The concrete expressions for $g_{\Phi tt}, g_{\Phi bb}, g_{\Phi \tilde{t}_i \tilde{t}_i}, g_{\Phi \tilde{b}_i \tilde{b}_i}$, ($i = 1, 2$) can be found in the Refs. [57, 93], and the concrete expressions of $g_{\Phi t_{(i+3)} t_{(i+3)}}, g_{\Phi b_{(i+3)} b_{(i+3)}}, g_{\Phi \tilde{\mathcal{U}}_i \tilde{\mathcal{U}}_i}$, as well as $g_{\Phi \tilde{\mathcal{D}}_i \tilde{\mathcal{D}}_i}$ are collected in Appendix B.

The form factors $A_{1/2}(x), A_0(x)$ in Eq. (41) are defined as

$$\begin{aligned} A_{1/2}(x) &= 2[x + (x-1)g(x)]/x^2, \\ A_0(x) &= -(x - g(x))/x^2, \end{aligned} \quad (42)$$

with

$$g(x) = \begin{cases} \arcsin^2 \sqrt{x}, & x \leq 1 \\ -\frac{1}{4} \left[\ln \frac{1+\sqrt{1-1/x}}{1-\sqrt{1-1/x}} - i\pi \right]^2, & x > 1. \end{cases} \quad (43)$$

For the CP-odd scalar $\Phi = A^0, A_B^0$, the decay width is written as

$$\Gamma_{NP}(\Phi \rightarrow gg) = \frac{G_F \alpha_s^2 m_\Phi^3}{64\sqrt{2}\pi^3} \left| \sum_q g_{\Phi qq} A'_{1/2}(x_q) \right|^2, \quad (44)$$

with

$$A'_{1/2}(x) = 2g(x)/x. \quad (45)$$

In the SM, the LO contributions to the diphoton decay of Higgs are derived from the one loop diagrams containing virtual charged gauge boson W^\pm or virtual top quarks. Whereas in

the BLMSSM, the exotic fermions $t_{4,5}$, $b_{4,5}$, $e_{4,5}$ together with their supersymmetric partners contribute the corrections to the diphoton decay width of CP-even neutral scalar at LO, the corresponding expression is written as

$$\begin{aligned}\Gamma_{NP}(\Phi \rightarrow \gamma\gamma) = & \frac{G_F \alpha^2 m_\Phi^3}{128\sqrt{2}\pi^3} \left| \sum_f N_c Q_f^2 g_{\Phi ff} A_{1/2}(x_f) + g_{\Phi WW} A_1(x_W) \right. \\ & + g_{\Phi H^+ H^-} \frac{m_W^2}{m_{H^\pm}^2} A_0(x_{H^\pm}) + \sum_{i=1}^2 g_{\Phi \chi_i^+ \chi_i^-} \frac{m_W}{m_{\chi_i}} A_{1/2}(x_{\chi_i}) \\ & \left. + \sum_{\tilde{f}} N_c Q_f^2 g_{\Phi \tilde{f} \tilde{f}} \frac{m_Z^2}{m_{\tilde{f}}^2} A_0(x_{\tilde{f}}) \right|^2, \quad (46)\end{aligned}$$

where $g_{h^0 WW} = \sin(\beta - \alpha)$, $g_{H^0 WW} = \cos(\beta - \alpha)$, and $g_{h_B^0 WW} = g_{H_B^0 WW} = 0$, the loop function A_1 is

$$A_1(x) = -[2x^2 + 3x + 3(2x - 1)g(x)]/x^2. \quad (47)$$

The concrete expressions for $g_{h^0(H^0)\chi_i^+\chi_i^-}$, $g_{h^0(H^0)H^+H^-}$ and the couplings between the lightest neutral CP-even Higgs and exotic leptons/sleptons can also be found in literature [57]. Furthermore one has $g_{h_B^0\chi_i^+\chi_i^-} = g_{H_B^0\chi_i^+\chi_i^-} = 0$, $g_{h_B^0 H^+H^-} = g_{H_B^0 H^+H^-} = 0$.

Similarly the decays $\Phi \rightarrow Z\gamma$ ($\Phi = h^0, H^0, h_B^0, H_B^0$) are induced through loops involving massive charged particles which couple to the scalar Φ , those corresponding decay widths are formulated as

$$\begin{aligned}\Gamma_{NP}(\Phi \rightarrow Z\gamma) = & \frac{G_F \alpha^2 m_\Phi^3}{64\sqrt{2}s_W^2 \pi^3} \left(1 - \frac{m_Z^2}{m_\Phi^2}\right)^2 \left| 2 \sum_f N_c Q_f \frac{T_f^{3L} - 2Q_f s_W^2}{c_W} g_{\Phi ff} A_{1/2}^h(x_f, y_f) \right. \\ & + g_{\Phi WW} A_1^h(x_W, y_W) + \frac{2c_W^2 - 1}{2c_W^2} g_{\Phi H^+ H^-} \frac{m_W^2}{m_{H^\pm}^2} A_0^h(x_{H^\pm}, y_{H^\pm}) \\ & + \sum_{i=1}^2 \sum_{\alpha=L,R} \frac{m_W}{m_{\chi_i}} g_{\Phi \chi_i^+ \chi_i^-}^\alpha g_{Z \chi_i^+ \chi_i^-}^\beta A_{1/2}^h(x_{\chi_i}, y_{\chi_i}) \\ & \left. + \sum_{\tilde{f}} N_c Q_f \frac{T_f^{3L} - Q_f s_W^2}{c_W} g_{\Phi \tilde{f} \tilde{f}} \frac{m_Z^2}{m_{\tilde{f}}^2} A_0^h(x_{\tilde{f}}, y_{\tilde{f}}) \right|^2, \quad (48)\end{aligned}$$

where $y_i = m_Z^2/(4m_i^2)$, and $T_f^{3L} = \pm 1/2$ denotes the 3rd component of weak isospin of corresponding matter field. For convenience the form factors are written as

$$A_0^h(x, y) = I_1(x, y),$$

$$\begin{aligned}
A_{1/2}^h(x, y) &= I_1(x, y) - I_2(x, y) , \\
A_1^h(x, y) &= c_w \left\{ 4 \left(3 - \frac{s_w^2}{c_w^2} \right) I_2(x, y) + \left[(1 + 2x) \frac{s_w^2}{c_w^2} - (5 + 2x) \right] I_1(x, y) \right\} , \quad (49)
\end{aligned}$$

with

$$\begin{aligned}
I_1(x, y) &= -\frac{1}{2(x-y)} + \frac{g(x) - g(y)}{2(x-y)^2} + \frac{y(f(x) - f(y))}{2(x-y)^2} , \\
I_2(x, y) &= \frac{g(x) - g(y)}{2(x-y)} , \\
f(x) &= \begin{cases} \sqrt{x-1} \arcsin^2 \sqrt{1/x}, & x \leq 1 \\ \frac{\sqrt{1-x}}{2} \left[\ln \frac{1+\sqrt{1-x}}{1-\sqrt{1-x}} - i\pi \right]^2, & x > 1 . \end{cases} \quad (50)
\end{aligned}$$

Generally the signature of this decay mode is drowned in the huge background from $q\bar{q} \rightarrow Z\gamma$ [95, 96] and $gg \rightarrow Z\gamma$ [97].

The LO diphoton decay width of the CP-odd neutral scalar $\Phi = A^0, A_B^0$ ($\Phi \rightarrow \gamma\gamma$) is formulated as

$$\Gamma_{NP}(\Phi \rightarrow \gamma\gamma) = \frac{G_F \alpha^2 m_\Phi^3}{128 \sqrt{2} \pi^3} \left| \sum_f N_c Q_f^2 g_{\Phi f f} A'_{1/2}(x_f) + \sum_{i=1}^2 g_{\Phi \chi_i^+ \chi_i^-} \frac{m_w}{m_{\chi_i}} A'_{1/2}(x_{\chi_i}) \right|^2 . \quad (51)$$

In a similar way, we can write down the decay widths for $\Phi \rightarrow Z\gamma$ for $\Phi = A^0, A_B^0$ as

$$\begin{aligned}
\Gamma_{NP}(\Phi \rightarrow Z\gamma) &= \frac{G_F \alpha^2 m_\Phi^3}{64 \sqrt{2} s_w^2 \pi^3} \left(1 - \frac{m_Z^2}{m_\Phi^2} \right)^2 \left| 2 \sum_f N_c Q_f \frac{T_f^{3L} - 2Q_f s_w^2}{c_w} g_{\Phi f f} A_{1/2}^a(x_f, y_f) \right. \\
&\quad \left. + \sum_{i=1}^2 \sum_{\alpha=L,R} \frac{m_w}{m_{\chi_i}} g_{\Phi \chi_i^+ \chi_i^-}^\alpha g_{Z \chi_i^+ \chi_i^-}^\beta A_{1/2}^a(x_{\chi_i}, y_{\chi_i}) \right|^2 , \quad (52)
\end{aligned}$$

with $A_{1/2}^a(x, y) = I_2(x, y)$.

The neutral scalar with mass around 750 GeV would decay through the modes $\Phi \rightarrow ZZ$, $\Phi \rightarrow WW$, $\Phi \rightarrow \bar{t}t$, where Z/W denote the on-shell neutral/charged electroweak gauge bosons and the corresponding widths are: [95, 98–100]

$$\begin{aligned}
\Gamma_{NP}(\Phi \rightarrow \bar{t}t) &= \frac{3G_F m_t^2}{4\sqrt{2}\pi} |g_{\Phi \bar{t}t}|^2 m_\Phi \beta_t^{p(\Phi)} \left[1 + \frac{4\alpha_s}{3\pi} \Delta_\Phi(\beta_t) \right], \\
\Gamma_{NP}(\Phi \rightarrow WW) &= \frac{G_F}{8\sqrt{2}\pi} m_\Phi^3 |g_{\Phi WW}|^2 \sqrt{1-x_w} (1-x_w + \frac{3}{4}x_w^2) \left[1 + 0.175 \frac{G_F m_\Phi^2}{\sqrt{2}\pi^2} \right], \\
\Gamma_{NP}(\Phi \rightarrow ZZ) &= \frac{G_F}{16\sqrt{2}\pi} m_\Phi^3 |g_{\Phi ZZ}|^2 \sqrt{1-x_z} (1-x_z + \frac{3}{4}x_z^2) \left[1 + 0.175 \frac{G_F m_\Phi^2}{\sqrt{2}\pi^2} \right] , \quad (53)
\end{aligned}$$

with $g_{h^0 ZZ} = g_{h^0 WW}$, and $x_V = 4m_V^2/m_\Phi^2$ ($V = W, Z$). Meanwhile the radiative corrections

$$\Delta_\Phi(\beta_t) = \begin{cases} \frac{1}{\beta_t} A(\beta_t) + \frac{1}{16\beta_t^3} (3 + 34\beta_t^2 - 13\beta_t^4) \ln \frac{1+\beta_t}{1-\beta_t} + \frac{3}{8\beta_t^2} (7\beta_t^2 - 1), \Phi = H^0, h_B^0, H_B^0 \\ \frac{1}{\beta_t} A(\beta_t) + \frac{1}{16\beta_t^3} (19 + 2\beta_t^2 + 3\beta_t^4) \ln \frac{1+\beta_t}{1-\beta_t} + \frac{3}{8\beta_t^2} (7 - \beta_t^2), \Phi = A^0, A_B^0 \end{cases} \quad (54)$$

with $\beta_t^2 = 1 - 4m_t^2/m_\Phi^2$, $p(H^0) = p(h_B^0) = p(H_B^0) = 3$, $p(A^0) = p(A_B^0) = 1$, and

$$\begin{aligned} A(\beta_t) = (1 + \beta_t^2) & \left[4Li_2\left(\frac{1 - \beta_t}{1 + \beta_t}\right) + 2Li_2\left(\frac{\beta_t - 1}{1 + \beta_t}\right) + 3 \ln \frac{1 - \beta_t}{1 + \beta_t} \ln \frac{2}{1 + \beta_t} \right. \\ & \left. + 2 \ln \frac{1 - \beta_t}{1 + \beta_t} \ln \beta_t \right] - 4\beta_t \ln \frac{4\beta_t^{4/3}}{1 - \beta_t^2}. \end{aligned} \quad (55)$$

The loop induced couplings $g_{\Phi tt}$, $g_{\Phi ZZ}$, $g_{\Phi WW}$ ($\Phi = h_B^0, H_B^0, A_B^0$) are given in Appendix C.

Considering the fact that no 750 GeV diphoton excess was observed at 8 TeV run of LHC [101, 102] but an excess shows up at 13 TeV [1, 2], we should determine that the heavy scalar most likely is produced via gluon fusion at 13 TeV. Therefore, the observed signals for the scalar diphoton excess at the LHC can be quantified as

$$\begin{aligned} \mu_{13\text{TeV}}^\Phi &= \sigma(gg \rightarrow \Phi) \text{BR}(\Phi \rightarrow \gamma\gamma) \\ &= \sigma(gg \rightarrow \Phi) \Gamma_{NP}(\Phi \rightarrow \gamma\gamma) / \Gamma_\Phi^{\text{tot}}. \end{aligned} \quad (56)$$

The total decay width of Φ is

$$\begin{aligned} \Gamma_\Phi^{\text{tot}} &= \Gamma_{NP}(\Phi \rightarrow gg) + \Gamma_{NP}(\Phi \rightarrow \gamma\gamma) + \Gamma_{NP}(\Phi \rightarrow Z\gamma) \\ &+ \Gamma_{NP}(\Phi \rightarrow ZZ) + \Gamma_{NP}(\Phi \rightarrow WW) + \Gamma_{NP}(\Phi \rightarrow \bar{t}t) + \Gamma_{NP}^{\text{other}}, \end{aligned} \quad (57)$$

where $\Gamma_{NP}^{\text{other}}$ denotes the width for other decay modes of Φ . Due that $\sigma(gg \rightarrow \Phi) \propto \Gamma(\Phi \rightarrow gg)$, we could have

$$\sigma(gg \rightarrow \Phi) = \frac{\Gamma_{NP}(\Phi \rightarrow gg)}{\Gamma_{NP}(h^0 \rightarrow gg)} \sigma(gg \rightarrow h^0)|_{m_{h^0} \simeq 750 \text{ GeV}}, \quad (58)$$

where $\sigma(gg \rightarrow h^0) \approx 0.85 \times 10^3 \text{ fb}$ [103, 104]. The combined value of 8 and 13 TeV measurements roughly is [5]

$$\mu_{13\text{TeV}}^{\text{exp}} = (4.4 \pm 1.1) \text{ fb}. \quad (59)$$

In the following numerical calculation, we will take into account the combined experimental value at 3σ as a simply guideline.

IV. NUMERICAL ANALYSES

To proceed our numerical discussion, we choose relevant parameters of the SM as [90]

$$\begin{aligned}\alpha_s(m_Z) &= 0.118, \quad \alpha(m_Z) = 1/128, \quad s_w^2(m_Z) = 0.23, \\ m_t &= 174.2 \text{ GeV}, \quad m_b = 4.2 \text{ GeV}, \quad m_w = 80.4 \text{ GeV}.\end{aligned}\tag{60}$$

As aforementioned, the most stringent constraint on the parameter space is that the 2×2 mass square matrix in Eq. (33) whose lightest eigenvector must be of a mass $m_{h_0} \simeq 125.09 \pm 0.24$ GeV. In order to obtain the final results satisfying this constraint, we require the tree level mass of CP-odd Higgs m_{A^0} to be

$$m_{A^0}^2 = \frac{m_{h_0}^2 (m_z^2 - m_{h_0}^2 + \Delta_{11} + \Delta_{22}) - m_z^2 \Delta_A + \Delta_{12}^2 - \Delta_{11} \Delta_{22}}{-m_{h_0}^2 + m_z^2 \cos^2 2\beta + \Delta_B},\tag{61}$$

where

$$\begin{aligned}\Delta_A &= \sin^2 \beta \Delta_{11} + \cos^2 \beta \Delta_{22} + \sin 2\beta \Delta_{12}, \\ \Delta_B &= \cos^2 \beta \Delta_{11} + \sin^2 \beta \Delta_{22} + \sin 2\beta \Delta_{12}.\end{aligned}\tag{62}$$

In order to avoid Landau singularities of $g_{B,L}$ below the Planck scale, we choose $B_4 = L_4 = 0$, $g_B(\Lambda_{NP}) = 0.35$, $g_L(\Lambda_{NP}) = 0.2$ with $\Lambda_{NP} = 3$ TeV. Meanwhile we assume $m_{Z_B} = m_{Z_L} = 1$ TeV to coincide with experimental data of searching additional neutral gauge bosons in colliders [90]. As discussed above, the plausible candidates for the 750 GeV resonance are h_B^0 and A_B^0 in this model. Since there is no correction from exotic leptons and their superpartners to the diphoton channels $h_B^0 \rightarrow 2\gamma$, $A_B^0 \rightarrow 2\gamma$ at leading order, moreover the corrections from exotic leptons and their superpartners to $h^0 \rightarrow 2\gamma$ are negligible if those particle masses are of order TeVs. In view of this, we could choose $\tan \beta_L = 2$, $\lambda_L = \lambda_E = \lambda_N = 0.5$, $m_{\tilde{L}_{4,5}} = m_{\tilde{\nu}_{4,5}} = m_{\tilde{E}_{4,5}} = 3$ TeV, $A_{\nu_{4,5}} = A_{e_{4,5}} = 500$ GeV in our numerical analyses. In order to predict the mass of h^0 falling in the range $124 \text{ GeV} \leq m_{h_0} \leq 126 \text{ GeV}$, we take $m_{\tilde{Q}_3} = 1$ TeV, $m_{\tilde{U}_3} = m_{\tilde{D}_3} = 2$ TeV, $A_t = 2.1$ TeV, $A_b = -1$ TeV, $Y_{d_4} = Y_{d_5} = 0.7 Y_b$, and $\tan \beta = 1.5$ unless a particular specification being made.

If we interpret the 750 GeV resonance as the CP-even scalar h_B^0 , we find that the signal $\mu_{13\text{TeV}}^{h_B^0} \leq \mathcal{O}(10^{-1} \text{ fb})$ through scanning the parameter space of the model, because there is

a cancellation between corrections from exotic quarks charged $2/3$ and that charged $-1/3$. However the cancelation does not appear as we interpret the 750 GeV resonance as the CP-odd scalar A_B^0 with a mass around 750 GeV which can account for the signal on diphoton excess at 750 GeV observed by the ATLAS and CMS collaborations simultaneously. Thus we choose the CP-odd scalar A_B^0 as the heavy boson and keep $m_{A_B^0} = 750$ GeV in the following.

In CP-conserving circumstances the decay channels $A_B^0 \rightarrow \gamma\gamma, gg$ are not affected by those parameters originating from scalar quark sectors at leading order, we take the parameters of corresponding squarks sector as

$$\begin{aligned} m_{\tilde{Q}_4} &= m_{\tilde{U}_4} = m_{\tilde{D}_4} = m_{\tilde{Q}_5} = m_{\tilde{U}_5} = m_{\tilde{D}_5} = 3 \text{ TeV} , \\ A_{u_4} &= A_{d_4} = A_{u_5} = A_{d_5} = 100 \text{ GeV} , \\ A_{BQ} &= A_{BU} = A_{BD} = 1 \text{ TeV} . \end{aligned} \tag{63}$$

Under our above assumptions on parameter space, we always take

$$m_2 = 700 \text{ GeV} , \quad \mu_B = 500 \text{ GeV} , \quad \mu = -800 \text{ GeV} , \tag{64}$$

since those parameters affect our theoretical evaluations mildly. Then, the free parameters affecting strongly our numerical results are

$$\lambda_Q, \lambda_U, \lambda_D, \tan\beta, \tan\beta_B, Y_{u_4}, Y_{u_5} . \tag{65}$$

Taking $Y_{u_4} = 0.2 Y_t$, $Y_{u_5} = 0.4 Y_t$, $\tan\beta = 1.5$, and $\tan\beta_B = 3$, we plot the signal $\mu_{13\text{TeV}}^{A_B} [\text{fb}]$ (solid line for $\lambda_U = \lambda_D = 0.3$ and dashed line for $\lambda_U = \lambda_D = 0.4$) versus parameter λ_Q in Fig. 1(a), where gray area denotes the experimental permission at 3σ deviations shown in Eq. (59). The numerical result indicates that the signal $\mu_{13\text{TeV}}^{A_B}$ is consistent with the experimental data as $1 \leq \lambda_Q \leq 2.7$ for $\lambda_U = \lambda_D = 0.3$ and $1.4 \leq \lambda_Q \leq 4$ for $\lambda_U = \lambda_D = 0.4$. We can see that the signal $\mu_{13\text{TeV}}^{A_B}$ turns stronger along with increasing of λ_Q for the couplings in Eq. (B5) are proportional to λ_Q . On the contrary, the signal $\mu_{13\text{TeV}}^{A_B}$ turns smaller along with increasing of $\lambda_{U,D}$ since the mass of the lightest vector-like quark charged $2/3$ is proportional to λ_U , and that of the lightest vector-like quark charged $-1/3$ is proportional to λ_D , respectively. In Fig. 1(b), we show the signal strength of the 125 GeV Higgs $R_{\gamma\gamma}$

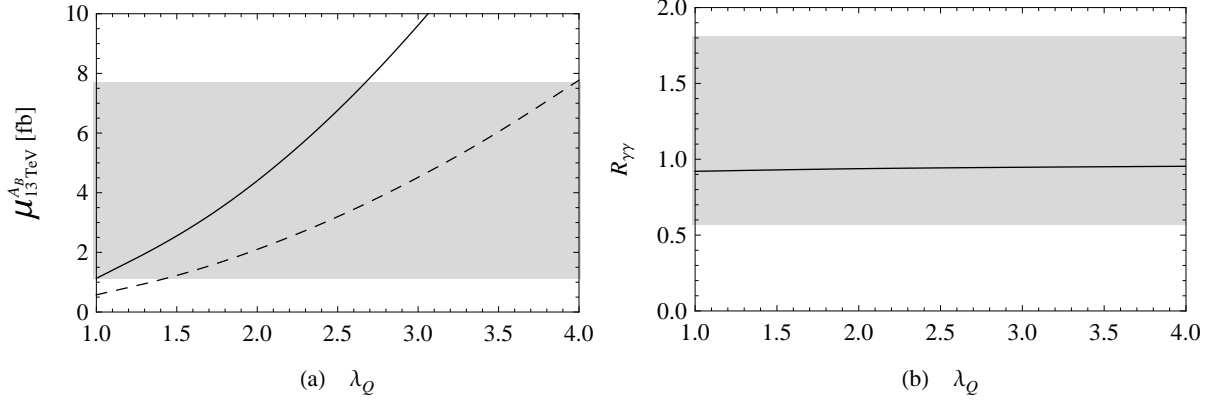


FIG. 1: As $Y_{u_4} = 0.2 Y_t$, $Y_{u_5} = 0.4 Y_t$, $\tan \beta = 1.5$, and $\tan \beta_B = 3$, (a) $\mu_{13\text{TeV}}^{A_B}$ [fb] (solid line for $\lambda_U = \lambda_D = 0.3$ and dashed line for $\lambda_U = \lambda_D = 0.4$) varies with the parameter λ_Q where gray area denotes the experimental permission at 3σ deviations in Eq. (59), (b) $R_{\gamma\gamma}$ (for $\lambda_U = \lambda_D = 0.3$) varies with the parameter λ_Q where gray area denotes the experimental permission at 2σ deviations in Eq. (38), respectively.

varying with the parameter λ_Q for $\lambda_U = \lambda_D = 0.3$, where gray area denotes the experimental permission at 2σ deviations in Eq. (38). We can see that the signal strength $R_{\gamma\gamma}$ is gentle with increasing of λ_Q . The results indicate that the signal strength $R_{\gamma\gamma}$ is consistent with the experimental data. Similarly the signal strength R_{VV^*} can also fit the experimental data in Eq. (38). The numerical results implicate that the signal strength $R_{\gamma\gamma}$ also depends on the parameters λ_U and λ_D mildly, actually the theoretical evaluations on $R_{\gamma\gamma}$ varying with the parameter λ_Q for $\lambda_U = \lambda_D = 0.4$ almost overlap with that for $\lambda_U = \lambda_D = 0.3$.

In addition, the ATLAS and CMS collaborations showed that in Run I stage no significant excesses were observed in the channels of 750 GeV Higgs decaying into ZZ [105], WW [106, 107] and $Z\gamma$ [108]. As generally believed, gluon fusion is responsible for the production of the Higgs boson which later may decay into those final states, thus the data of LHC at 8 TeV set upper bounds on the ratios as [6]

$$\frac{\Gamma(\Phi \rightarrow Z\gamma)}{\Gamma(\Phi \rightarrow \gamma\gamma)} < 2, \quad \frac{\Gamma(\Phi \rightarrow ZZ)}{\Gamma(\Phi \rightarrow \gamma\gamma)} < 6, \quad \frac{\Gamma(\Phi \rightarrow WW)}{\Gamma(\Phi \rightarrow \gamma\gamma)} < 20. \quad (66)$$

In the chosen parameter space of the BLMSSM model, $A_B^0 \rightarrow ZZ(WW)$ appears at one-loop

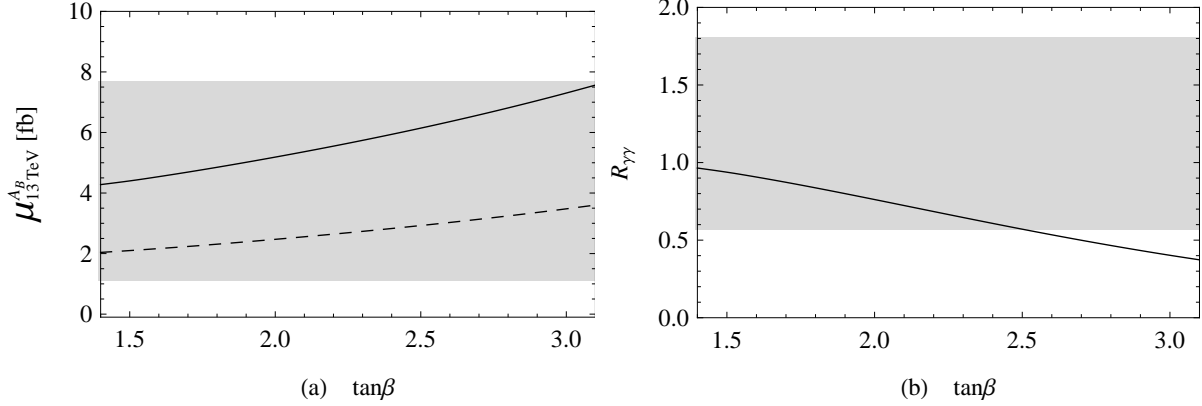


FIG. 2: As $Y_{u_4} = 0.2 Y_t$, $Y_{u_5} = 0.4 Y_t$, $\lambda_Q = 2$, and $\tan \beta_B = 3$, (a) $\mu_{13\text{TeV}}^{A_B}$ (solid line for $\lambda_U = \lambda_D = 0.3$ and dashed line for $\lambda_U = \lambda_D = 0.4$) varies with the parameter $\tan \beta$ where gray area denotes the experimental permission at 3σ deviations in Eq. (59), and (b) $R_{\gamma\gamma}$ (for $\lambda_U = \lambda_D = 0.3$) varies with the parameter $\tan \beta$ where gray area denotes the experimental permission at 2σ deviations in Eq. (38), respectively.

level and we have obtained the relevant ratios as

$$\frac{\Gamma(A_B^0 \rightarrow Z\gamma)}{\Gamma(A_B^0 \rightarrow \gamma\gamma)} \sim \mathcal{O}(10^{-1}), \quad \frac{\Gamma(A_B^0 \rightarrow ZZ)}{\Gamma(A_B^0 \rightarrow \gamma\gamma)} \sim \mathcal{O}(10^{-1}), \quad \frac{\Gamma(A_B^0 \rightarrow WW)}{\Gamma(A_B^0 \rightarrow \gamma\gamma)} \sim \mathcal{O}(1), \quad (67)$$

which confirm the bounds presented in Eq. (66). In this model, the decay mode $\Gamma_{NP}(A_B^0 \rightarrow t\bar{t})$ can only occur via two-loop diagrams, so its rate is smaller than the width of diphoton channel. Since, as generally expected, the 750 GeV resonance is produced via gluon fusion, there is a large probability it would decay into two gluons which turn into di-jet. In this work, the numerical result indicates that $\Gamma(A_B^0 \rightarrow gg)/\Gamma(A_B^0 \rightarrow \gamma\gamma) \sim \mathcal{O}(10^2) < 1300$, which accommodates the di-jet research at Run I [6, 109, 110].

Besides the parameter λ_Q , the parameter $\tan \beta$ existing in the MSSM also affects our numerical evaluations strongly. Choosing $Y_{u_4} = 0.2 Y_t$, $Y_{u_5} = 0.4 Y_t$, $\lambda_Q = 2$, and $\tan \beta_B = 3$, we depict in Fig. 2(a) the signal $\mu_{13\text{TeV}}^{A_B}$ (solid line for $\lambda_U = \lambda_D = 0.3$ and dashed line for $\lambda_U = \lambda_D = 0.4$) versus $\tan \beta$ where gray area denotes the experimental permission at 3σ deviations in Eq. (59), and Fig. 2(b) the signal strength $R_{\gamma\gamma}$ (for $\lambda_U = \lambda_D = 0.3$) versus $\tan \beta$ where gray area denotes the experimental permission at 2σ deviations in Eq. (38),

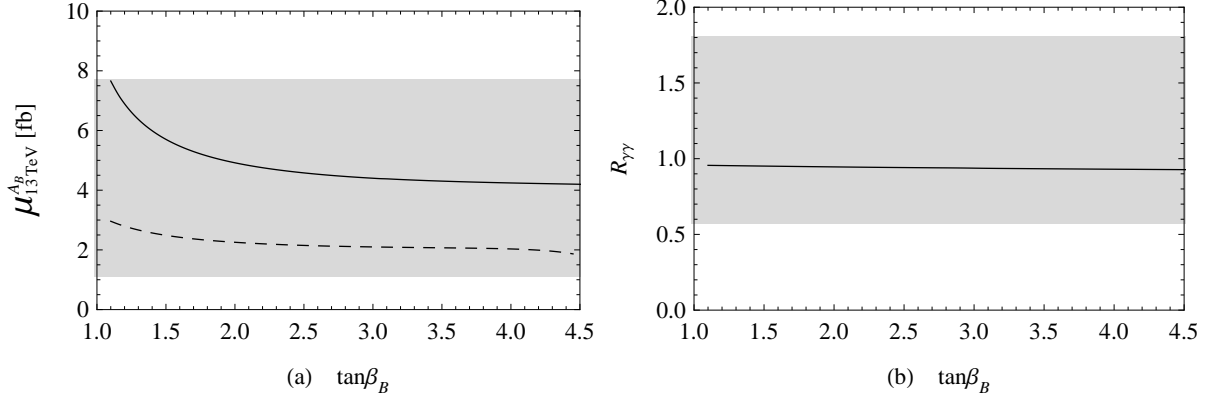


FIG. 3: As $Y_{u_4} = 0.2 Y_t$, $Y_{u_5} = 0.4 Y_t$, $\tan\beta = 1.5$, and $\lambda_Q = 2$, (a) $\mu_{13\text{TeV}}^A$ (solid line for $\lambda_U = \lambda_D = 0.3$ and dashed line for $\lambda_U = \lambda_D = 0.4$) varies with the parameter $\tan\beta_B$ where gray area denotes the experimental permission at 3σ deviations in Eq. (59), and (b) $R_{\gamma\gamma}$ (for $\lambda_U = \lambda_D = 0.3$) varies with the parameter $\tan\beta_B$ where gray area denotes the experimental permission at 2σ deviations in Eq. (38), respectively.

respectively. Fig. 2(a) shows that the signal $\mu_{13\text{TeV}}^A$ turns large as $\tan\beta$ increasing. When the parameter $\tan\beta > 3.1$ as $\lambda_U = \lambda_D = 0.3$, the signal $\mu_{13\text{TeV}}^A$ exceeds the upper bound. For $\lambda_U = \lambda_D = 0.4$, the signal $\mu_{13\text{TeV}}^A$ is coincide with the experimental data at 3σ deviations. With increasing of $\tan\beta$, the signal strength $R_{\gamma\gamma}$ decreases. As $\tan\beta > 2.5$ and $\lambda_U = \lambda_D = 0.3$, we cannot account for the experimental results for the signal strength of the 125 GeV Higgs $R_{\gamma\gamma}$, showed in Fig. 2(b). In other words, the simultaneous interpretation of experimental data on the decays of the heavy scalar with 750 GeV and the lightest Higgs with 125 GeV similarly favors relatively small value of $\tan\beta$ under our assumptions on the parameter space.

Additional the parameter $\tan\beta_B$ in this model also affects our numerical results strongly. In Fig. 3, we investigate (a) the signal strength $\mu_{13\text{TeV}}^A$ (solid line for $\lambda_U = \lambda_D = 0.3$ and dashed line for $\lambda_U = \lambda_D = 0.4$) and (b) the signal strength $R_{\gamma\gamma}$ (for $\lambda_U = \lambda_D = 0.3$) varying with the parameter $\tan\beta_B$, where $Y_{u_4} = 0.2 Y_t$, $Y_{u_5} = 0.4 Y_t$, $\tan\beta = 1.5$, and $\lambda_Q = 2$. It is seen that the signal strength $\mu_{13\text{TeV}}^A$ decreases steeply as $\tan\beta_B < 2$, and decreases mildly as $\tan\beta_B > 2$. As for the signal strength $R_{\gamma\gamma}$ varies with $\tan\beta_B$ slowly.

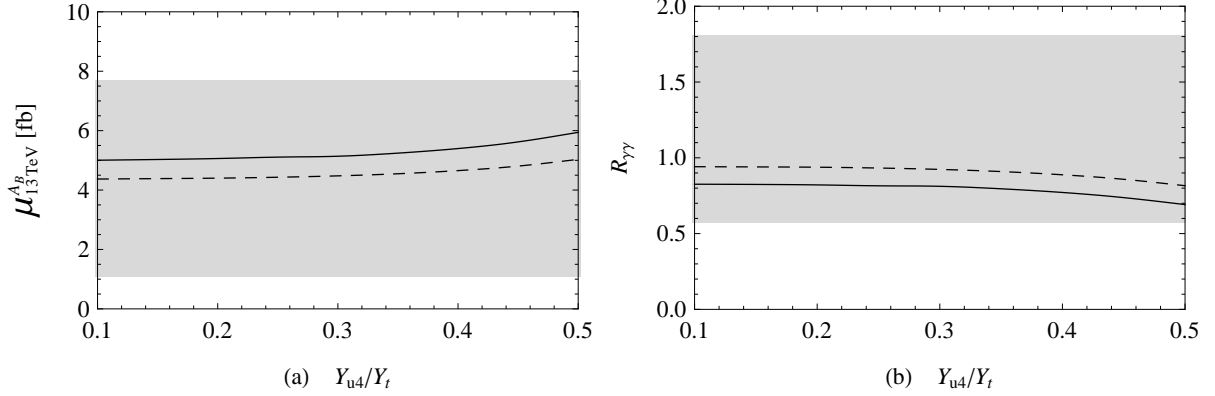


FIG. 4: As $\lambda_U = \lambda_D = 0.3$, $\lambda_Q = 2$, $\tan\beta = 1.5$, and $\tan\beta_B = 3$, (a) $\mu_{13\text{TeV}}^{A_B}$ varies with the parameter Y_{u_4} where gray area denotes the experimental permission at 3σ deviations in Eq. (59), and (b) $R_{\gamma\gamma}$ varies with the parameter Y_{u_4} where gray area denotes the experimental permission at 2σ deviations in Eq. (38), respectively. Here, the dashed line stands for $Y_{u_5} = 0.4 Y_t$, the solid line stands for $Y_{u_5} = 0.6 Y_t$.

At the last, we investigate the Yukawa couplings of the fourth and fifth generation up-type quark $Y_{u_{4,5}}$ in Fig. 4. Taking $\lambda_U = \lambda_D = 0.3$, $\lambda_Q = 2$, $\tan\beta = 1.5$ and $\tan\beta_B = 3$, we plot the signal strength $\mu_{13\text{TeV}}^{A_B}$ versus Y_{u_4} in (a) and the signal strength $R_{\gamma\gamma}$ vs Y_{u_4} in (b) of Fig. 4, where the dashed line stands for $Y_{u_5} = 0.4 Y_t$ and the solid line stands for $Y_{u_5} = 0.6 Y_t$, respectively. With increasing of Y_{u_4} , the signal strength $\mu_{13\text{TeV}}^{A_B}$ turns stronger, on the other hand the signal strength $R_{\gamma\gamma}$ turns small. In other words the large Yukawa couplings Y_{u_5} affects our numerical evaluations on the signal strength $\mu_{13\text{TeV}}^{A_B}$ and the signal strength $R_{\gamma\gamma}$ simultaneously.

V. SUMMARY

The discovery of 750 GeV boson at the diphoton channel is very inspiring because it may be a signal for new physics BSM. People are excited and tempted to try various models in hand to investigate the case and see if the model with a certain parameter range can give a reasonable interpretation. We argue that an extension of the supersymmetric model with

gauged baryon and lepton numbers might be able to account for the experimental data on 750 GeV diphoton excess reported by ATLAS and CMS recently based on its success in earlier phenomenological studies.

Indeed, even though the 750 GeV boson is observed in the diphoton channel as a resonance, there are still many puzzles about its eccentric behaviors are not well understood yet. The first challenge is its unusually large width about 45 GeV reported by ATLAS while CMS shows that it could be small. And it is also reported that this resonance is not seen at the WW , ZZ , and $t\bar{t}$ channels. It implies that it has some decay channels which are not experimental observed yet, secondly, its coupling to the regular SM particles must be very suppressed, or just as the diphoton channel the effective coupling to SM particles is realized via loops inside which only heavy BSM particles exist.

In this BLMSSM, because the scalar h_L^0, H_L^0, A_L^0 do not have couplings to the exotic quarks at tree level, they can be ruled out for being a candidate of the scalar particle of $m_\phi = 750$ GeV observed at the diphoton channel. The contribution of H^0, A^0 and h_B^0 to the diphoton decay widths is too small to be responsible for the diphoton excess even though their mass were 750 GeV. By contrary, adopting an assumption on the relevant parameter space, the CP-odd scalar A_B^0 with 750 GeV mass in this model can account for the experimental data on the heavy scalar diphoton resonance observed by the ATLAS and CMS collaborations naturally. Simultaneously, this supersymmetric model can fit the 125 GeV Higgs data determined by the earlier run I at the LHC.

It is proposed that besides the diphoton channel the main decay portals are not to the SM particles, at least not at the tree level, instead, it may decay into dark matter which is BSM particles. Moreover, if the new physics scale is indeed at TeV, we have all reasons to expect observing more resonances (charged and neutral) with some strange behaviors which cannot be understood in the framework of the SM.

No doubt, the discovery of the diphoton excess at 750 GeV and confirmation of the 750 GeV resonance is a great breakthrough, but it is necessary to put more efforts to investigate relevant physics. If eventually the 750 GeV is firmly identified as a genuine particle which definitely is a BSM boson, a new world will be opened in front of us, especially, the project to build up the SPPC of 50~100 TeV in China should be more favorable and we are expecting

the new spring of high energy physics to come soon.

Acknowledgments

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Appendix A: The radiative corrections to the mass squared matrix from exotic quark fields

The one-loop radiative corrections from exotic quark fields are formulated as [111–119]

$$\begin{aligned}
\Delta_{11}^B = & \frac{3G_F Y_{u_4}^4 v^4}{4\sqrt{2}\pi^2 \sin^2 \beta} \cdot \frac{\mu^2 (A_{u_4} - \mu \cot \beta)^2}{(m_{\tilde{t}'_1}^2 - m_{\tilde{t}'_2}^2)^2} g(m_{\tilde{t}'_1}, m_{\tilde{t}'_2}) \\
& + \frac{3G_F Y_{u_5}^4 v^4}{4\sqrt{2}\pi^2 \cos^2 \beta} \left\{ \ln \frac{m_{\tilde{t}'_3} m_{\tilde{t}'_4}}{m_{\tilde{t}_5}^2} + \frac{A_{u_5} (A_{u_5} - \mu \tan \beta)}{m_{\tilde{t}'_3}^2 - m_{\tilde{t}'_4}^2} \ln \frac{m_{\tilde{t}'_3}^2}{m_{\tilde{t}'_4}^2} \right. \\
& + \left. \frac{A_{u_5}^2 (A_{u_5} - \mu \tan \beta)^2}{(m_{\tilde{t}'_3}^2 - m_{\tilde{t}'_4}^2)^2} g(m_{\tilde{t}'_3}, m_{\tilde{t}'_4}) \right\} \\
& + \frac{3G_F Y_{d_4}^4 v^4}{4\sqrt{2}\pi^2 \cos^2 \beta} \left\{ \ln \frac{m_{\tilde{b}'_1} m_{\tilde{b}'_2}}{m_{\tilde{b}_4}^2} + \frac{A_{d_4} (A_{d_4} - \mu \tan \beta)}{m_{\tilde{b}'_1}^2 - m_{\tilde{b}'_2}^2} \ln \frac{m_{\tilde{b}'_1}^2}{m_{\tilde{b}'_2}^2} \right. \\
& + \left. \frac{A_{d_4}^2 (A_{d_4} - \mu \tan \beta)^2}{(m_{\tilde{b}'_1}^2 - m_{\tilde{b}'_2}^2)^2} g(m_{\tilde{b}'_1}, m_{\tilde{b}'_2}) \right\} \\
& + \frac{3G_F Y_{d_5}^4 v^4}{4\sqrt{2}\pi^2 \sin^2 \beta} \cdot \frac{\mu^2 (A_{d_5} - \mu \cot \beta)^2}{(m_{\tilde{b}'_3}^2 - m_{\tilde{b}'_4}^2)^2} g(m_{\tilde{b}'_3}, m_{\tilde{b}'_4}), \tag{A1}
\end{aligned}$$

$$\Delta_{12}^B = \frac{3G_F Y_{u_4}^4 v^4}{8\sqrt{2}\pi^2 \sin^2 \beta} \cdot \frac{\mu (-A_{u_4} + \mu \cot \beta)}{m_{\tilde{t}'_1}^2 - m_{\tilde{t}'_2}^2} \left\{ \ln \frac{m_{\tilde{t}'_1}}{m_{\tilde{t}'_2}} + \frac{A_{u_4} (A_{u_4} - \mu \cot \beta)}{m_{\tilde{t}'_1}^2 - m_{\tilde{t}'_2}^2} g(m_{\tilde{t}'_1}, m_{\tilde{t}'_2}) \right\}$$

$$\begin{aligned}
& + \frac{3G_F Y_{u_5}^4 v^4}{8\sqrt{2}\pi^2 \cos^2 \beta} \cdot \frac{\mu(-A_{u_5} + \mu \tan \beta)}{m_{\tilde{t}'_3}^2 - m_{\tilde{t}'_4}^2} \left\{ \ln \frac{m_{\tilde{t}'_3}}{m_{\tilde{t}'_4}} + \frac{A_{u_5}(A_{u_5} - \mu \tan \beta)}{m_{\tilde{t}'_3}^2 - m_{\tilde{t}'_4}^2} g(m_{\tilde{t}'_3}, m_{\tilde{t}'_4}) \right\} \\
& + \frac{3G_F Y_{d_4}^4 v^4}{8\sqrt{2}\pi^2 \cos^2 \beta} \cdot \frac{\mu(-A_{d_4} + \mu \tan \beta)}{m_{\tilde{d}'_1}^2 - m_{\tilde{d}'_2}^2} \left\{ \ln \frac{m_{\tilde{d}'_1}}{m_{\tilde{d}'_2}} + \frac{A_{d_4}(A_{d_4} - \mu \tan \beta)}{m_{\tilde{d}'_1}^2 - m_{\tilde{d}'_2}^2} g(m_{\tilde{d}'_1}, m_{\tilde{d}'_2}) \right\} \\
& + \frac{3G_F Y_{d_5}^4 v^4}{8\sqrt{2}\pi^2 \sin^2 \beta} \cdot \frac{\mu(-A_{d_5} + \mu \cot \beta)}{m_{\tilde{b}'_3}^2 - m_{\tilde{b}'_4}^2} \left\{ \ln \frac{m_{\tilde{b}'_3}}{m_{\tilde{b}'_4}} + \frac{A_{d_5}(A_{d_5} - \mu \cot \beta)}{m_{\tilde{b}'_3}^2 - m_{\tilde{b}'_4}^2} g(m_{\tilde{b}'_3}, m_{\tilde{b}'_4}) \right\},
\end{aligned} \tag{A2}$$

$$\begin{aligned}
\Delta_{22}^B = & \frac{3G_F Y_{u_4}^4 v^4}{4\sqrt{2}\pi^2 \sin^2 \beta} \left\{ \ln \frac{m_{\tilde{t}'_1} m_{\tilde{t}'_2}}{m_{t_4}^2} + \frac{A_{u_4}(A_{u_4} - \mu \cot \beta)}{m_{\tilde{t}'_1}^2 - m_{\tilde{t}'_2}^2} \ln \frac{m_{\tilde{t}'_1}^2}{m_{\tilde{t}'_2}^2} \right. \\
& + \frac{A_{u_4}^2 (A_{u_4} - \mu \cot \beta)^2}{(m_{\tilde{t}'_1}^2 - m_{\tilde{t}'_2}^2)^2} g(m_{\tilde{t}'_1}, m_{\tilde{t}'_2}) \left. \right\} \\
& + \frac{3G_F Y_{u_5}^4 v^4}{4\sqrt{2}\pi^2 \cos^2 \beta} \cdot \frac{\mu^2 (A_{u_5} - \mu \tan \beta)^2}{(m_{\tilde{t}'_3}^2 - m_{\tilde{t}'_4}^2)^2} g(m_{\tilde{t}'_3}, m_{\tilde{t}'_4}) \\
& + \frac{3G_F Y_{d_4}^4 v^4}{4\sqrt{2}\pi^2 \cos^2 \beta} \cdot \frac{\mu^2 (A_{d_4} - \mu \tan \beta)^2}{(m_{\tilde{b}'_1}^2 - m_{\tilde{b}'_2}^2)^2} g(m_{\tilde{b}'_1}, m_{\tilde{b}'_2}) \\
& + \frac{3G_F Y_{d_5}^4 v^4}{4\sqrt{2}\pi^2 \sin^2 \beta} \left\{ \ln \frac{m_{\tilde{b}'_3} m_{\tilde{b}'_4}}{m_{b_5}^2} + \frac{A_{d_5}(A_{d_5} - \mu \cot \beta)}{m_{\tilde{b}'_3}^2 - m_{\tilde{b}'_4}^2} \ln \frac{m_{\tilde{b}'_3}^2}{m_{\tilde{b}'_4}^2} \right. \\
& + \frac{A_{d_5}^2 (A_{d_5} - \mu \cot \beta)^2}{(m_{\tilde{b}'_3}^2 - m_{\tilde{b}'_4}^2)^2} g(m_{\tilde{b}'_3}, m_{\tilde{b}'_4}) \left. \right\},
\end{aligned} \tag{A3}$$

here $v = \sqrt{v_u^2 + v_d^2} \simeq 246$ GeV and

$$g(x, y) = 1 - \frac{x^2 + y^2}{x^2 - y^2} \ln \frac{x}{y}. \tag{A4}$$

To derive the results presented above, we adopt the appropriate assumptions $|\lambda_Q v_B|, |\lambda_U \bar{v}_B|, |\lambda_D \bar{v}_B| \gg |Y_{u_4} v|, |Y_{u_5} v|, |Y_{d_4} v|, |Y_{d_5} v|$ in our calculation.

Appendix B: The couplings between heavy Higgs and exotic quarks/squarks

$$g_{H^{0_{t(i+3)} t(i+3)}} = -\frac{\sqrt{2} m_W s_W}{e m_{t(i+3)}} \left[Y_{u_4} (W_t^\dagger)_{i2} (U_t)_{1i} \sin \alpha - Y_{u_5} (W_t^\dagger)_{i1} (U_t)_{2i} \cos \alpha \right],$$

$$\begin{aligned}
g_{H^0 b_{(i+3)} b_{(i+3)}} &= \frac{\sqrt{2} m_W s_W}{e m_{b_{(i+3)}}} \left[Y_{d_4} (W_b^\dagger)_{i2} (U_b)_{1i} \cos \alpha + Y_{d_5} (W_b^\dagger)_{i1} (U_b)_{2i} \sin \alpha \right], \\
g_{H^0 \tilde{u}_i \tilde{u}_i} &= -\frac{s_W c_W}{e m_Z} \left[\xi_{u_{ii}}^S \sin \alpha + \xi_{d_{ii}}^S \cos \alpha \right], \quad (i = 1, 2, 3, 4), \\
g_{H^0 \tilde{D}_i \tilde{D}_i} &= -\frac{s_W c_W}{e m_Z} \left[\eta_{u_{ii}}^S \sin \alpha + \eta_{d_{ii}}^S \cos \alpha \right], \quad (i = 1, 2, 3, 4). \tag{B1}
\end{aligned}$$

$$\begin{aligned}
g_{h_B^0 t_{(i+3)} t_{(i+3)}} &= \frac{\sqrt{2} m_W s_W}{e m_{t_{(i+3)}}} \left[\lambda_U (W_t^\dagger)_{i2} (U_t)_{2i} \cos \alpha_B - \lambda_Q (W_t^\dagger)_{i1} (U_t)_{1i} \sin \alpha_B \right], \\
g_{h_B^0 b_{(i+3)} b_{(i+3)}} &= \frac{\sqrt{2} m_W s_W}{e m_{b_{(i+3)}}} \left[\lambda_D (W_b^\dagger)_{i2} (U_b)_{2i} \cos \alpha_B + \lambda_Q (W_b^\dagger)_{i1} (U_b)_{1i} \sin \alpha_B \right], \\
g_{h_B^0 \tilde{u}_i \tilde{u}_i} &= -\frac{s_W c_W}{e m_Z} \left[\zeta_{u_{ii}}^S \cos \alpha_B - \zeta_{d_{ii}}^S \sin \alpha_B \right], \quad (i = 1, 2, 3, 4), \\
g_{h_B^0 \tilde{D}_i \tilde{D}_i} &= -\frac{s_W c_W}{e m_Z} \left[\zeta_{u_{ii}}^S \cos \alpha_B - \zeta_{d_{ii}}^S \sin \alpha_B \right], \quad (i = 1, 2, 3, 4). \tag{B2}
\end{aligned}$$

$$\begin{aligned}
g_{H_B^0 t_{(i+3)} t_{(i+3)}} &= \frac{\sqrt{2} m_W s_W}{e m_{t_{(i+3)}}} \left[\lambda_U (W_t^\dagger)_{i2} (U_t)_{2i} \sin \alpha_B + \lambda_Q (W_t^\dagger)_{i1} (U_t)_{1i} \cos \alpha_B \right], \\
g_{H_B^0 b_{(i+3)} b_{(i+3)}} &= \frac{\sqrt{2} m_W s_W}{e m_{b_{(i+3)}}} \left[\lambda_D (W_b^\dagger)_{i2} (U_b)_{2i} \sin \alpha_B + \lambda_Q (W_b^\dagger)_{i1} (U_b)_{1i} \cos \alpha_B \right], \\
g_{H_B^0 \tilde{u}_i \tilde{u}_i} &= -\frac{s_W c_W}{e m_Z} \left[\zeta_{u_{ii}}^S \sin \alpha_B + \zeta_{d_{ii}}^S \cos \alpha_B \right], \quad (i = 1, 2, 3, 4), \\
g_{H_B^0 \tilde{D}_i \tilde{D}_i} &= -\frac{s_W c_W}{e m_Z} \left[\zeta_{u_{ii}}^S \sin \alpha_B + \zeta_{d_{ii}}^S \cos \alpha_B \right], \quad (i = 1, 2, 3, 4). \tag{B3}
\end{aligned}$$

$$\begin{aligned}
g_{A^0 t_{(i+3)} t_{(i+3)}} &= -\frac{\sqrt{2} m_W s_W}{e m_{t_{(i+3)}}} \left[Y_{u_4} (W_t^\dagger)_{i2} (U_t)_{1i} \cos \beta + Y_{u_5} (W_t^\dagger)_{i1} (U_t)_{2i} \sin \beta \right], \\
g_{A^0 b_{(i+3)} b_{(i+3)}} &= \frac{\sqrt{2} m_W s_W}{e m_{b_{(i+3)}}} \left[Y_{d_4} (W_b^\dagger)_{i2} (U_b)_{1i} \sin \beta - Y_{d_5} (W_b^\dagger)_{i1} (U_b)_{2i} \cos \beta \right]. \tag{B4}
\end{aligned}$$

$$\begin{aligned}
g_{A_B^0 t_{(i+3)} t_{(i+3)}} &= -\frac{\sqrt{2} m_W s_W}{e m_{t_{(i+3)}}} \left[\lambda_U (W_t^\dagger)_{i2} (U_t)_{2i} \cos \beta_B - \lambda_Q (W_t^\dagger)_{i1} (U_t)_{1i} \sin \beta_B \right], \\
g_{A_B^0 b_{(i+3)} b_{(i+3)}} &= \frac{\sqrt{2} m_W s_W}{e m_{b_{(i+3)}}} \left[\lambda_D (W_b^\dagger)_{i2} (U_b)_{2i} \sin \beta_B + \lambda_Q (W_b^\dagger)_{i1} (U_b)_{1i} \cos \beta_B \right]. \tag{B5}
\end{aligned}$$

Here, we adopt the abbreviation $s_W \equiv \sin \theta_W$ with θ_W being the Weinberg angle. Furthermore, e is the electromagnetic coupling constant, and the concrete expressions of $\xi_{u_{ii}}^S$, $\xi_{d_{ii}}^S$, $\eta_{u_{ii}}^S$, $\eta_{d_{ii}}^S$ can be found in Ref. [61].

Appendix C: The loop induced couplings

The loop induced couplings $g_{\Phi ZZ}$, $g_{\Phi WW}$ ($\Phi = h_B^0, H_B^0, A_B^0$) are written as

$$\begin{aligned}
g_{h_B^0 WW} = & \frac{eY_{u_4}\lambda_Q v_u}{4(4\pi)^2 s_W m_W} \sin \alpha_B \left(\frac{11}{6} + \ln \frac{\lambda_Q^2 v_B^2}{\Lambda_{NP}^2} \right) \\
& + \frac{eY_{u_5}\lambda_U v_d}{4(4\pi)^2 s_W m_W} \cos \alpha_B \left(\frac{11}{6} + \ln \frac{\lambda_U^2 \bar{v}_B^2}{\Lambda_{NP}^2} \right) \\
& + \frac{eY_{d_4}\lambda_Q v_d}{4(4\pi)^2 s_W m_W} \sin \alpha_B \left(\frac{11}{6} + \ln \frac{\lambda_Q^2 v_B^2}{\Lambda_{NP}^2} \right) \\
& + \frac{eY_{d_5}\lambda_D v_u}{4(4\pi)^2 s_W m_W} \cos \alpha_B \left(\frac{11}{6} + \ln \frac{\lambda_D^2 \bar{v}_B^2}{\Lambda_{NP}^2} \right) \\
& - \frac{B_4 e g_B^2}{4(4\pi)^2 s_W m_W} (v_B \sin \alpha_B + \bar{v}_B \cos \alpha_B) \left(2 + \ln \frac{m_{\tilde{Q}_4}^2}{\Lambda_{NP}^2} \right) \\
& + \frac{(1+B_4) e g_B^2}{4(4\pi)^2 s_W m_W} (v_B \sin \alpha_B + \bar{v}_B \cos \alpha_B) \left(2 + \ln \frac{m_{\tilde{Q}_5}^2}{\Lambda_{NP}^2} \right), \tag{C1} \\
g_{h_B^0 ZZ} = & \frac{eY_{u_4}\lambda_Q v_u}{36(4\pi)^2 s_W c_W m_Z} (3-4s_W^2)^2 \sin \alpha_B \left(\frac{11}{6} + \ln \frac{\lambda_Q^2 v_B^2}{\Lambda_{NP}^2} \right) \\
& + \frac{eY_{u_5}\lambda_U v_d}{36(4\pi)^2 s_W c_W m_Z} (3-4s_W^2)^2 \cos \alpha_B \left(\frac{11}{6} + \ln \frac{\lambda_U^2 \bar{v}_B^2}{\Lambda_{NP}^2} \right) \\
& + \frac{eY_{d_4}\lambda_Q v_d}{36(4\pi)^2 s_W c_W m_Z} (3-2s_W^2)^2 \sin \alpha_B \left(\frac{11}{6} + \ln \frac{\lambda_Q^2 v_B^2}{\Lambda_{NP}^2} \right) \\
& + \frac{eY_{d_5}\lambda_D v_u}{36(4\pi)^2 s_W c_W m_Z} (3-2s_W^2)^2 \cos \alpha_B \left(\frac{11}{6} + \ln \frac{\lambda_D^2 \bar{v}_B^2}{\Lambda_{NP}^2} \right) \\
& - \frac{B_4 e g_B^2}{4(4\pi)^2 s_W c_W m_Z} \left(2 - 4s_W^2 + \frac{20}{9}s_W^4 \right) (v_B \sin \alpha_B \\
& + \bar{v}_B \cos \alpha_B) \left(2 + \ln \frac{m_{\tilde{Q}_4}^2}{\Lambda_{NP}^2} \right) \\
& + \frac{(1+B_4) e g_B^2}{4(4\pi)^2 s_W c_W m_Z} \left(2 - 4s_W^2 + \frac{20}{9}s_W^4 \right) (v_B \sin \alpha_B \\
& + \bar{v}_B \cos \alpha_B) \left(2 + \ln \frac{m_{\tilde{Q}_5}^2}{\Lambda_{NP}^2} \right) \\
& + \frac{4B_4 e g_B^2 s_W^3}{9(4\pi)^2 c_W m_Z} (v_B \sin \alpha_B + \bar{v}_B \cos \alpha_B) \left(2 + \ln \frac{m_{\tilde{U}_4}^2}{\Lambda_{NP}^2} \right)
\end{aligned}$$

$$\begin{aligned}
& + \frac{B_4 e g_B^2 s_W^3}{9(4\pi)^2 c_W m_Z} (v_B \sin \alpha_B + \bar{v}_B \cos \alpha_B) \left(2 + \ln \frac{m_{\tilde{D}_4}^2}{\Lambda_{NP}^2}\right) \\
& - \frac{4(1+B_4) e g_B^2 s_W^3}{9(4\pi)^2 c_W m_Z} (v_B \sin \alpha_B + \bar{v}_B \cos \alpha_B) \left(2 + \ln \frac{m_{\tilde{U}_5}^2}{\Lambda_{NP}^2}\right) \\
& - \frac{(1+B_4) e g_B^2 s_W^3}{9(4\pi)^2 c_W m_Z} (v_B \sin \alpha_B + \bar{v}_B \cos \alpha_B) \left(2 + \ln \frac{m_{\tilde{D}_5}^2}{\Lambda_{NP}^2}\right), \tag{C2}
\end{aligned}$$

$$g_{H_B^0 WW} = g_{h_B^0 WW} (\sin \alpha_B \rightarrow -\cos \alpha_B, \cos \alpha_B \rightarrow \sin \alpha_B), \tag{C3}$$

$$g_{H_B^0 ZZ} = g_{h_B^0 ZZ} (\sin \alpha_B \rightarrow -\cos \alpha_B, \cos \alpha_B \rightarrow \sin \alpha_B), \tag{C4}$$

$$\begin{aligned}
g_{A_B^0 WW} &= \frac{ieY_{u_4} \lambda_Q v_u}{4(4\pi)^2 s_W m_W} \sin \beta_B \left(\frac{11}{6} + \ln \frac{\lambda_Q^2 v_B^2}{\Lambda_{NP}^2}\right) \\
&+ \frac{ieY_{u_5} \lambda_U v_d}{4(4\pi)^2 s_W m_W} \cos \beta_B \left(\frac{11}{6} + \ln \frac{\lambda_U^2 \bar{v}_B^2}{\Lambda_{NP}^2}\right) \\
&+ \frac{ieY_{d_4} \lambda_Q v_d}{4(4\pi)^2 s_W m_W} \sin \beta_B \left(\frac{11}{6} + \ln \frac{\lambda_Q^2 v_B^2}{\Lambda_{NP}^2}\right) \\
&+ \frac{ieY_{d_5} \lambda_D v_u}{4(4\pi)^2 s_W m_W} \cos \beta_B \left(\frac{11}{6} + \ln \frac{\lambda_D^2 \bar{v}_B^2}{\Lambda_{NP}^2}\right), \tag{C5}
\end{aligned}$$

$$\begin{aligned}
g_{A_B^0 ZZ} &= \frac{ieY_{u_4} \lambda_Q v_u}{36(4\pi)^2 s_W c_W m_Z} (3 - 4s_W^2)^2 \sin \beta_B \left(\frac{11}{6} + \ln \frac{\lambda_Q^2 v_B^2}{\Lambda_{NP}^2}\right) \\
&+ \frac{ieY_{u_5} \lambda_U v_d}{36(4\pi)^2 s_W c_W m_Z} (3 - 4s_W^2)^2 \cos \beta_B \left(\frac{11}{6} + \ln \frac{\lambda_U^2 \bar{v}_B^2}{\Lambda_{NP}^2}\right) \\
&+ \frac{ieY_{d_4} \lambda_Q v_d}{36(4\pi)^2 s_W c_W m_Z} (3 - 2s_W^2)^2 \sin \beta_B \left(\frac{11}{6} + \ln \frac{\lambda_Q^2 v_B^2}{\Lambda_{NP}^2}\right) \\
&+ \frac{ieY_{d_5} \lambda_D v_u}{36(4\pi)^2 s_W c_W m_Z} (3 - 2s_W^2)^2 \cos \beta_B \left(\frac{11}{6} + \ln \frac{\lambda_D^2 \bar{v}_B^2}{\Lambda_{NP}^2}\right). \tag{C6}
\end{aligned}$$

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